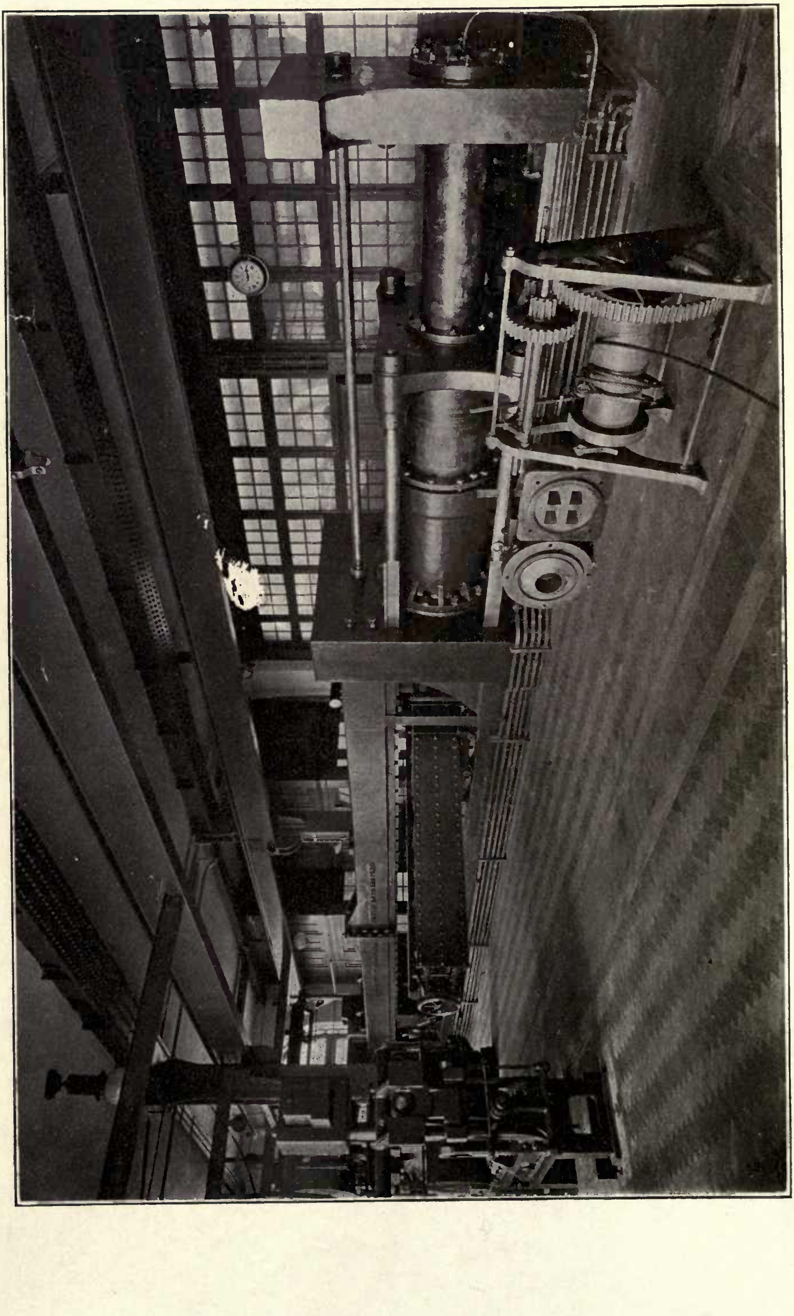
A HANDBOOK OF TESTING MATERIALS



A HANDBOOK OF TESTING

BY

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MATERIALS

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PREFACE TO THE SECOND EDITION

DURING the past five years engineers all over the world have been so fully occupied with their ordinary and extraordinary work that few engineering text-books have been written. The author has been stationed in the Far East since 1912, and the urgent request of the publishers for a new edition were made when it was impossible to give the time necessary for recasting the contents. It was therefore decided to issue the present new edition with a few necessary minor alterations. An addition has also been made to the data concerning timber. The illustrations remain as before; they have proved helpful to students and are perhaps of interest to engineers in practice.

The war stimulated the spirit of scientific investigation and it emphasised the necessity of testing the materials used in engineering work. This new edition may therefore be of assistance to the thousands of engineering students who are receiving instruction in the English language in all parts of the world, and also to qualified engineers in practice.

C. A. M. S.

PREFACE TO FIRST EDITION

All technical colleges, and many of the large engineering works, now possess a laboratory furnished with apparatus for the testing of materials. It is hoped that some portion of this book may be of service to engineers engaged in practice; it is, however, written primarily for the college student, although a great engineer has said that one of the attractions of our work is that we are *always* students in engineering. If, at times, the reader thinks that the descriptions of apparatus, or of tests, are somewhat detailed, he should remember that, although he may be quite familiar with a machine or process, other readers, possibly, have not had the same opportunities.

The chief object of the author has been to interest engineers in experimental work. The experience gained in four colleges, and a works testing department, has led to the belief that the great importance of experimental work is not sufficiently recognised. It is hoped that students may be stimulated to look up, both before and after they have made experiments, the description of the apparatus and tests mentioned. The diagrams will perhaps be useful for sketching purposes.

The methods of teaching engineering vary in the different centres. No attempt is made in this book to standardise such methods—each instructor is the best judge of what suits the plant and the students. A list of experiments is given in Chapter XII., as it may be useful to those who are commencing to organise a laboratory course.

The illustrations have been made especially for the book. Attention has been given to the scheming, as well as the actual drawing and reproduction of diagrams, in the hope that the details of the apparatus described may be made clear. An effort has been made to avoid catalogue illustrations. In some places—especially in the chapter on

alternating stress machines—the diagrams used in the Proceedings of Societies and technical papers have been replaced by others drawn with the object of showing principles rather than details of construction. In the Appendices there are included discussions on certain researches, which have been included for the advanced student. Some of these researches are so recent that they have not been previously described in a text-book on materials. Further experiments may be suggested to the reader by a study of the methods used and results obtained.

The number of instructors in college laboratories are frequently insufficient for their arduous duties. It is suggested that the book will assist the instructors and students by reason of the various experiments, methods, and data recorded. It is advisable to take a group of not more than ten students and explain the apparatus to be used to them. It is usually inconvenient to take notes during such demonstrations, and the contents of the book may therefore be useful to the student for reference purposes. During the conduct of the ordinary laboratory work the most suitable number to be engaged on one experiment is (usually) three. Suggestions are given in the Introduction concerning the record of such work.

The author begs to thank numerous friends who have discussed the contents of the book for their assistance. His assistant, Mr. V. C. Davies, B.Sc., has not only carefully read through the proofs, but made many useful suggestions concerning the contents of the book. Mr. E. J. Surman, B.Sc., has also helped to revise the proofs. It is therefore hoped that the book is free from misprints, etc., but the author would be glad to hear of any that are noticed by readers. The following have kindly granted permission for the extracts from their publications, viz.: editors of technical journals mentioned, British Engineering Standards Committee, Institution of Civil Engineers, Institution of Mechanical Engineers, Physical Society, etc.

C. A. M. S.

LONDON,
June, 1910.

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OF

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CHAPTER I

INTRODUCTION

Theory and Practice.—It is possible to learn a great deal of the science which underlies all engineering work by making tests and experiments. There is a continuous use, and adjustment to correct perspective, of results obtained by theory and practice. The work of testing materials is very largely of a practical nature. For commercial routine tests little is required beyond a knowledge of arithmetic and a skill in the manipulation of certain machines and measuring appliances. An engineering training is necessary if the correct deductions are to be made from the test. It must, however, be understood that commercial figures, although of great value to engineers, are not always the only results to be sought in making tests, and in commercial work it frequently happens that new tests and apparatus must be devised.

The properties of the materials used in structures and machines are of great importance. A knowledge of these properties can be best obtained by conducting a series of experiments upon specimens or samples of the various materials. In making these tests, the difference between work done in an engineering and a physics laboratory will at once become apparent. Although there is a certain

similarity between the methods employed, yet there will be noticed in the materials used and tested by engineers a variation in the properties of different samples of the same material. The object, therefore, of the experiments made upon steel, iron, copper, alloys, etc., is to find average values, rather than rigidly exact numerical results.

The properties of materials used by engineers vary owing to many causes. If we take a pound of almost any gas and measure its temperature, pressure, and volume, we can estimate with accuracy the behaviour of the gas, if it is to be compressed, under certain conditions, to a new pressure and volume. If, however, we take a pound of steel we cannot forecast with any accuracy the behaviour of the material under load if we know nothing more about it than the fact that it is called steel. It is of some assistance if we know the chemical composition of the steel, but, even with such information, we cannot estimate with accuracy the load which the material will carry at the point of fracture.

Experience has taught engineers that the only satisfactory method of estimating suitable loads in design works is to subject samples of the actual material to be used, to tests, which reproduce, as nearly as is possible, the conditions met with in actual practice. Thus, if a quantity of steel is made for a purpose in which the material is subjected to a direct pull, the most satisfactory way of deciding the maximum value of the pull to be allowed in practice is to test samples of the material under similar conditions, and obtain a record of the physical properties of these samples. Of course it is possible that all of the steel from which the samples have been selected will not behave in a similar fashion to the specimens tested. In general, however, we can obtain sufficient data to assist us to estimate with considerable certainty the safe loads to which the materials may be subjected.

In building a bridge, roof or other structure, or machine, there are two possible errors which may be made owing to a lack of knowledge of the materials employed. Insufficient material may be used, in which case there will probably be a

collapse. Too much material may be used, in which case the structure or machine will cost more than is necessary. Although generally it is not so obvious, yet the fault of the engineer who uses more material than is necessary is as great as that of the engineer who uses too little. All safe structures and machines use more material than is *theoretically* necessary, because a certain *factor of safety*, arrived at from the result of experience, is employed. The safe load must not, however, be reckoned too high or too low. The most satisfactory method of estimating the safe load is to test one or more specimens of the material to be used. From a commercial point of view that is the purpose of the science of the testing of materials. There are, however, other reasons why this work should be undertaken. These are outlined below.

The Testing of Materials Laboratory.—Instruction in the properties of materials is given in the laboratory for the following definite objects: (1) To demonstrate the behaviour of various materials under stress. (2) To establish clear conceptions as to the meaning of fundamental terms of the engineer's vocabulary, such as, yield-point, ultimate strength, modulus of elasticity, and shear modulus. (3) To make the student familiar with the methods by which materials are tested to obtain such numerical results as will enable their properties to be recorded and compared with other materials. (4) To fix in the memory a few average results for the materials more commonly used in engineering work. (5) To lay the foundation for a certain habit of thought, invaluable to the engineer. This might be called cultivating the habit of *testing* laws and materials (wherever it is possible to do so), instead of *accepting* them from authorities. (6) To give the student practice in writing reports of work done by himself. (7) To undertake original investigations (for publication) calculated to advance the knowledge of the strength and elasticity of materials.

The laboratory experiments, as a means of illustration, must go hand-in-hand with theoretical instruction. The latter will place before the student underlying principles. It will assist

him to understand, in their correct perspective, the maze of experimental facts which he will obtain during his own personal investigations. It will aid in developing habits of clear and discerning thought.

It frequently happens that students are eager and willing to conduct tests, but put off the working out of the results. No greater fallacy exists than that the test is completed and everything known when the actual experiment is finished. Numerical results should, whenever it is convenient to do so, be calculated in the laboratory. The slide-rule is sufficiently accurate. In many cases approximate results are sufficient. If that precaution is not taken it may happen that an afternoon's work will be wasted because of some fault of the material, apparatus, or observer, which would have been discovered immediately the first test was worked out.

The amount of time on each experiment varies with the individual student. It is usually necessary to spend a good deal of time upon any subject of which it is desired to have a full knowledge. The student should not consider it irksome or unnecessary to repeat experiments.

While a multiplicity of experiments may be very attractive —especially when they are varied—yet it is possible that labour which appears to be mere drudgery may be of the greatest educational value. There is a great deal of what people who possess no enthusiasm for their work call drudgery in the life of the engineer. "Staying power" is often the best characteristic, in the laboratory or in the works of a reliable man.

The object of the laboratory is not to pump into the student's mind a large amount of information, but to cultivate in that mind the ability to reason, to plan and scheme out experiments. In order, however, to thoroughly understand underlying principles, routine work must be done. Originality will be useless unless combined with a knowledge of fundamental laws. Discipline is essential in the laboratory, as elsewhere, and the student must subordinate his own ideas until the opportunity presents itself for their presentation.

That laboratory instruction is essential is now no longer doubted. The equipment in all of the centres of higher education in this country is growing each year; in some it might almost be called magnificent. The whole tendency of the work is to arouse interest. It appeals to the eye and the sense of touch in a way impossible to obtain in the class-room. In the University of London Engineering Examinations (for internal students) marks are given for the laboratory work. There is a growing tendency in the same direction in the provinces. Each of the students, who takes the examination in the strength of materials, presents a book containing a report of the tests which he has made. It might be an advantage if the laboratory rough note-book were also inspected. In any case, the student's ability is judged from his record of laboratory instruction. It is advisable, therefore, for this to be neatly compiled.

At the end of this book is a chapter dealing with the experiments which are usually undertaken for the purposes of these examinations. Those actually performed must of necessity depend upon the equipment of the particular laboratory in which the student is working and the time which he is able to give to this branch of study.

Possibly in some laboratories opportunities will occur for the more advanced students to undertake special investigations. It is suggested that some of the researches alluded to in this book may serve as a guide to that end.

The Report of the Test.—The writing up of the report of the experiment is by no means the least important portion of the work. Unfortunately, very few people express their thoughts in an intelligible fashion. There are men of great technical ability whose writings do not always contain clear expression of their thoughts. It is to be hoped that the twentieth century system of training for engineers will alter that in time. Clear expression should be the natural outcome of clear thinking. Every engineering student will be called upon, at some period in his career, to furnish a report upon a technical subject. It is probable that the report will be read

by those who know little or nothing of technical work. The client may be, for instance, a solicitor, banker, financier, or a journalist. He will be influenced by the manner in which the report is written. Most of us who have to write upon technical subjects live to regret that we had but little training in the art of composition in our student days. Lucidity is the mental lubricant which so many of us lack. In writing up the report of any test there is an opportunity for neatness and clearness of expression. It should be composed as if for a client who knows nothing whatever about the subject.

There is a great temptation to occupy considerable space with a dissertation upon this subject of writing the report. It is with difficulty resisted. Let the student remember that a shop labourer can put a piece of material in the testing machine and break it. It requires a competent engineer to conduct, and report upon, a test such as is needed for commercial purposes.

CHAPTER II

GENERAL PROPERTIES OF MATERIALS

Ductile and Brittle Materials.—The materials used in engineering work are roughly divided into two classes, viz., ductile and brittle. It is difficult to say whether some materials should be considered as ductile or brittle, as there is no decided line of demarcation. The past history of the material will affect its properties.

Ductility may be defined as the ease with which a metal can be elongated into a wire by being drawn through the gradually diminishing holes of the wire-drawer's plate. In general, for testing purposes, we call a material ductile when it stretches perceptibly before fracture during a tension test.

A gauge of this property called ductility is supplied if we calculate the percentage elongation of the material, and also the percentage reduction in area of the fracture, after the test is completed.

We can group together a number of metals which are ductile. Steel, the material most generally used in engineering work, varies considerably in composition and in mechanical properties. There is the steel which can be used as tie-rods or crankshafts, and there is the steel used for castings. The problem is more complicated each year by the discovery and introduction of steel alloys. Again, steel and its alloys are extremely sensitive to mechanical working and temperature treatment. The physical properties may be completely changed by heating the material to a certain temperature and cooling slowly or suddenly. In general, we may say that the steel which has a low carbon constituent is ductile. The following metals are usually classified as ductile, viz., gold, silver, platinum, iron,[1]

[1] Certain types of iron (including steel in the general term iron).

nickel, copper, palladium, aluminium, zinc, tin, and lead. Metals which stretch imperceptibly before fracture during a tension test are said to be brittle. In general such metals are very strong in compression, weak in tension, and unsuitable to withstand shock.

The properties of the new alloys (which are constantly being discovered) are in many cases very remarkable. It is advisable, when testing any material, to obtain some rough idea before commencing the test as to its mechanical properties, otherwise damage to the instruments or shackles may result.

Chemical Analysis.—This is a branch of the subject which the average college student has little or no time to investigate. The skill and experience necessary for an exact and reliable analysis of steel or cast-iron, which are by far the most important materials, can only be gained by long specialisation. The only part of the subject which it is necessary for the engineer to know is how to prepare a sample for submitting to the chemist. This should be done as follows:—

Preparing Samples.—These should be in the form of fine turnings or drillings, but not dust. They must be perfectly free from all oil and other foreign substances.

Take a bar specimen and commence drilling in one side with a flat angled drill about $\frac{1}{2}$-inch diameter. When the top $\frac{1}{8}$ inch has been removed, shake out the drillings and prepare to make a proper sample. With a $\frac{1}{4}$-inch drill, bore into the specimen to a depth not exceeding $\frac{1}{2}$ inch. Repeat this in various parts of the bar, and collect together about 2 or 3 ounces of fine drillings. These should be at once placed in a clean test-tube or sample bottle, and handed on to the chemist who will carry out the analysis.

The usual iron and steel analysis will give as percentages: carbon, silicon, sulphur, phosphorus and manganese.

Structure of Materials.—In general, the appearance of the fractured surface of a bar of metal is an index of its character. An easy way of obtaining some idea of the properties of the material is by nicking a bar on one side with a chisel, gripping

it in a vice, and breaking it with a hammer. The brittleness or toughness, as well as the general strength of the material, is indicated by the angle through which it bends and the force required to break it. The appearance of the fracture should be noticed in all tests, and it is usually advisable to record it. The bar is said to be *crystalline* when made up of visible crystals, either coarse or fine. When the crystals are so fine that they cannot be noticed as crystals by the eye, the fracture is said to be *granular*. Sometimes the grains are so minute as to be called *silky*—as is the case with a tool steel properly hardened. Wrought-iron usually shows a fracture which has the appearance of the material breaking piecemeal, owing to the imperfect adhesion between the numerous microscopic slag-fibres and the iron and the great difference in the toughness of the two materials. The structure is called *fibrous*. Generally speaking, a coarsely crystalline or granular metal has less satisfactory working properties than one of the same class in which the fracture is finer. Incidentally, it may be noted that the size of the grain often largely depends upon the temperature at which the metal was cast, and upon the subsequent thermal and mechanical treatment.

The Microstructure of Materials.—Although the examination of metals under a microscope is a matter for the metallurgist rather than the engineer, this branch of the testing of materials has become of such importance during recent years that it is essential that the engineer engaged in the testing of materials should at least be able to follow the methods employed in this branch of metallography, and be able to judge something of the properties of a material from microphotographs prepared by an expert in that particular branch.

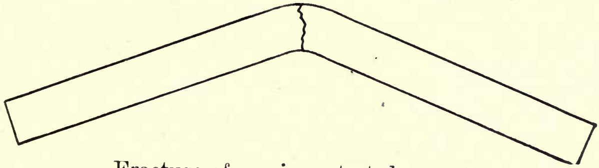
Like large numbers of other members of the mineral kingdom, the metals have a crystalline structure, formed when the metal solidifies or is subjected to certain mechanical treatment. In the impure state of the ordinary materials of construction, this crystalline condition is changed to give a peculiar but characteristic appearance to the material, when examined under the microscope. This depends on the exact

nature of the impurities and on the previous mechanical and heat treatment to which it has been subjected. This appearance is termed the microstructure.

The specimens to be examined are cut from the material to a convenient size suitable for holding in the fingers. The piece is then brought to a smooth surface by machining, grinding, or filling and smoothing up on several grades of emery cloth glued to a smooth block of hard wood. The finishing process is performed by polishing on a revolving polishing disc covered with chamois leather to which a small amount of jewellers' rouge has been applied.

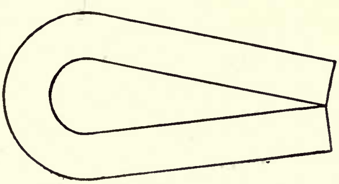
The specimen is then "etched" with a dilute acid solution or some other liquid which will attack the metal and preferably stain some parts different from others. When mounted on a microscope and illuminated with light directed normal to its surface the microstructure is clearly exhibited by a magnification of from 30 diameters upwards. When necessary for the purpose of keeping records photographs can be taken of the image by attaching a special form of camera to the eyepiece.

The examination is most important in connection with iron and steel, as it not only gives a rough idea of its composition, but also gives to the expert a good idea of the heat treatment which the steel has undergone; a point which it is obvious would be difficult, if not impossible, to determine by chemical analysis. Thus, in the case of iron containing 0·9 per cent. of carbon, if this steel is properly and carefully annealed a uniform product results known as pearlite, and when examined under the microscope is observed to consist of either uniform streaks of dark and light lines or similar granules, and derives its name from the play of colour on its surface, causing a slight resemblance to mother-of-pearl. When this is observed in the case of the particular steel mentioned it shows careful annealing. On the other hand, if this same sample was raised to a bright cherry red, and suddenly quenched in a freezing mixture of ice and salt, *i.e.*, an exaggerated case of bad heat treatment or a hardening process, the structure observed



Fracture of specimen tested as cast.

Micrographs of Cast Steel before and after annealing.
Magnified 28·5 diameters.



Specimen tested when annealed (no fracture).

PLATE I.

is known as martensite, and takes the form of interlacing needles quite different from pearlite. It might be mentioned that in the particular case we have chosen the martensite is known sometimes as hardenite, and is observed as the principal constituent of hardened steel.

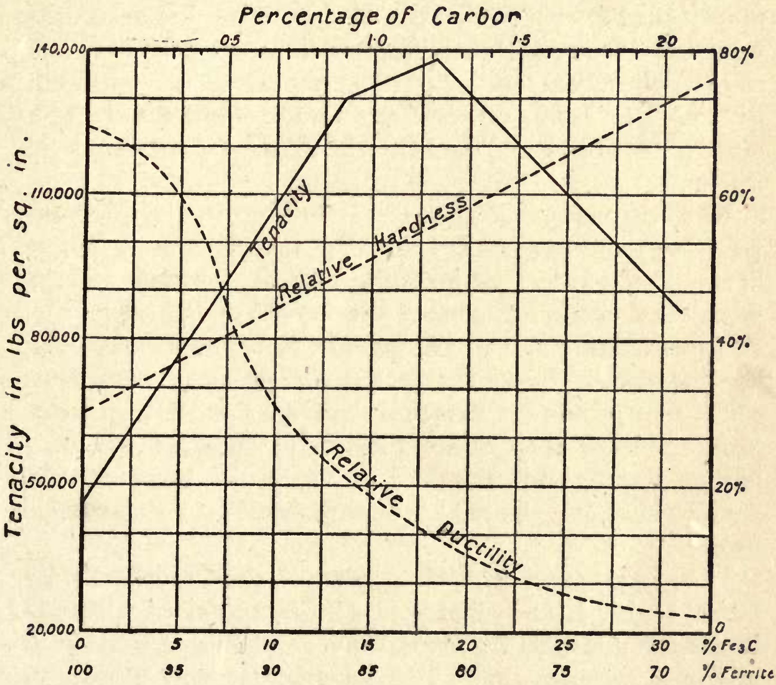


FIG. 1.—Curves showing Effect of varying Percentages of Carbon in Steel on the Tenacity, Hardness and Ductility of the Material.

The reason for these differences is largely due to the fact that (again referring to the particular case chosen) when cooled slowly the carbon and some of the iron combine to form what is considered a definite compound known by its appearance in the microscope as cementite, or chemically as iron carbide (Fe_3C), and containing 6·67 per cent. of carbon and pure iron, known in microstructure phraseology as ferrite. On the other hand, when cooled suddenly the steel

forms unsegregated pearlite, a combination of iron and carbon containing 0·9 per cent. of carbon which has crystallised without separating into carbide and ferrite. In this connection Howe has given a very instructive diagram showing the relation between the varying percentages of cementite and ferrite, such as occur in annealed specimens and the physical properties of the material. It should be noted that unless the specimen is annealed, while, of course, the percentage of carbon will remain the same, the percentage of cementite will be less. Fig. 1, taken from Howe's work, shows the effect on tenacity, hardness and ductility, of different percentages of carbon.

When the percentage of carbon is large (as in grey pig-iron) very slow cooling causes the carbon to separate into crystalline flakes, distinguished as graphite, and is observed in the microscope obtruding among the crystal grains of ferrite. The presence of sulphur, phosphorus, manganese, and silicon can likewise be recognised by the characteristic appearance which they give to the structure depending on the heat treatment. Marked changes are likewise produced in the non-ferrous metals, and annealed or hardened brass can be distinguished at a glance by the entire change of its crystalline nature.

Plate I., prepared from drawings and photographs kindly loaned by Dr. J. Arnold, of Sheffield University, will illustrate in a striking fashion the remarkable change brought about in cast steel by annealing. The top half (as cast) illustrates martensitic structure, while the lower half (annealed) illustrates pearlite structure. The change in mechanical properties will be readily seen from the drawings of a specimen, one bent before and the other after annealing.

Mechanical Properties.—The results of different tests made upon various materials show some remarkable contrasts. It is of advantage that the materials do not all possess the same properties, and it is obvious that while one material may be the most suitable for one purpose, it is quite unsuitable for another.

It is important to know, for any material, (*a*) the load at which it ceases to be elastic; (*b*) the maximum load before or at the point of fracture. In commercial testing (*a*) is usually taken as that load at which a large amount of stretch takes place and the beam drops. This point is usually called the *yield point*. In scientific testing there is some difficulty concerning this matter of elastic breakdown, and there are in use three terms which require explanation. They are:—

(1) *The Limit of Proportionality.*—This is usually taken as that point on the stress strain diagram where the increase in stretch is not exactly proportional to the increase in load. Obviously the exact point at which this takes place will depend upon the sensitiveness of the extensometer used to detect the stretch.

(2) *The Elastic Limit.*—If, when the weight is run back and there is no load on the specimen, the extensometer pointer returns to its original position at the starting of the test, there is said to be no *permanent set* upon the material. When such a permanent set is recorded we have reached the elastic limit. In many alloys there is such a gradual change from the elastic to the plastic state that it is essential to have some other criterion than the drop of the beam. In which case it is usual to record the load at which the permanent set is a certain definite amount, such as, say, $\frac{1}{100}$ part of an inch.

(3) *The Yield Point.*—This is usually taken as the load at which the drop of the beam is first noted.

Mild, or low carbon, steel usually shows all three points quite distinctly. At the critical point where elastic breakdown first takes place, however, the influence of time on the amount of stretch is so very marked that it seems probable that, under ideal conditions of loading and a perfectly homogeneous material, all three points would coincide.

In the practical use of materials the three characteristics—elastic limit (or yield point), breaking load, and extensibility—are of the first importance. It is not sufficient to know what weight a bar of metal will withstand without rupture; it is of

the utmost importance to ascertain what load it will bear without sensible distortion. A metal which must be shaped under a hammer may with advantage have a low elastic limit, so long as its extensibility is sufficient. Such a metal is usually *tough.* Hard steel is very strong, but its extensibility is slight, and the hardest kinds are liable to be broken under a sudden blow.

The Various Tests.—Although it is most usual to determine the tensile strength of a material, it is being gradually recognised that other tests are also essential. If a material is to be subjected to a push stress, then a compression test is the most satisfactory. Similarly, if a material is to be used in a shaft, where it is subjected to a twist, *a torsion test* should be made. At present there is no law for all materials which connects the strength in tension with that of the material in compression and torsion. It is quite possible to imagine a bar of metal which almost resembles a bundle of straws. It would be perfectly satisfactory if tested in tension, but fail utterly if subjected to torque or compression.

It often happens that materials are subjected to *alternating stresses* of push and pull. In which case the tests which reveal the properties suitable for such work are the alternating stress tests described later. Unfortunately such tests usually take a considerable time to carry out, and are therefore not generally conducted for commercial purposes, although their importance is now fully recognised.

Similarly, materials are in practice frequently subjected to combined loadings, such as torsion and thrust in a propeller shaft, and it is necessary to determine the loads which it is possible to safely carry. Tests made, however, under such conditions would be too expensive for commercial purposes, and it is left for researches to determine if static tests will suffice to allow us to estimate the loads to be carried.

Again, it happens on railways that the steel lines are subjected to heavy blows or to suddenly applied loads. In tension, compression bending, or torsion tests (or *static tests*, as they are called) the load should be applied very gradually and

steadily (any irregularity in the time of loading, or even irregularity of the speed at which the load is applied, will affect the results; hence the importance of adding equal increments of load during equal increments of time). But frequently materials (such as those used for rails or armour plate) are subjected to impact. A special form of testing machine is used for such tests.

Therefore the reader will see that various special tests are described for certain materials, and while the actual commercial value of such tests may be a matter for discussion, there can be no two opinions as to their advantage for a complete experimental study of the properties of materials used in engineering work.

CHAPTER III

MACHINES FOR TENSION, COMPRESSION, AND BENDING TESTS

The Usual Machine.—It is the usual practice to build a tensile testing machine so that it can be readily adapted to testing materials in compression or bending. Although this "omnibus" testing machine is of great advantage in a commercial laboratory, since it saves capital outlay, yet it is sometimes awkward in a college laboratory, because only one group of students can be at work doing one of the tests. Although the usual size of testing machine in colleges is from 50 tons to 100 tons, it is possible that for most of the experimental work done by the student a 10-ton machine is large enough, in which case there may be sufficient capital available for two or even three machines. However, if the reader grasps the principles of the "omnibus" machine, he will understand those used only for one of the tests. The above tests are enumerated, but it will be seen later that the "omnibus" testing machine is also used for other special tests.

Tensile Testing Machines.—The easiest way of obtaining the tensile strength of any material would be to take a rod of that material, suspend it in a vertical position from one end, and hang weights on the other end until it breaks. The aggregate of the weights suspended at that moment from the free end would form the breaking load for that particular bar. The cross-sectional area of the bar, being known, the breaking stress for that material could easily be deduced. In a similar manner the compressive or bending strength could be obtained. But this simple and crude method of obtaining the strength of materials could only be used where the bar tested had an extremely small cross-section, or else when the material itself was very weak. With ordinary materials, such as are

used in engineering practice, this method could not be adopted, as, with even small sizes of test bar, the weights required would be so large, and the labour of handling them so great, as to render its use in ordinary workshops or laboratories a practical impossibility. This difficulty, then, is overcome by the use of levers interposed between the point of action of the weight and the specimen whose strength we wish to determine. The interposition of this lever, or set of levers, makes the use of a smaller weight possible, and gives consequent facility in handling the machine, even when large powers are to be employed.

We will now sketch out a very simple form of testing machine. The specimen of the material to be tested consists of a truly turned cylindrical bar, one end of which is gripped in a pair of jaws fixed to the framework of the machine, and the other attached to the short end of a lever. On the long arm of this lever a weight is allowed to slide,[1] so that its distance from the fulcrum can be varied at will. We commence with the weight near the fulcrum, so that little or no pull is exerted on the specimen. The weight is then run out slowly towards the end of the arm, the load being thus gradually applied until the specimen breaks. The breaking load is then equal to the weight on the long arm, multiplied by its leverage, or by the ratio between the long and short arms of the lever. But here we encounter another difficulty. If the specimen always remained of the same length, the lever would always remain of the same effective length, as it would in all cases be horizontal. But on the application of a load, the specimen stretches, more or less, according to the nature of the material that is being tested. The lever thus assumes an oblique position and tends to bend, as well as to stretch the material. It is necessary, then, to take up the stretch in the material so as to keep the lever in a horizontal position. This is usually done either by means of a hydraulic ram or

[1] In some machines the weight is fixed in position but variable n amount. The load is applied by adding weights at the end of the long arm of the lever. The same result is obtained, but the other method is usually employed as the application of the load is thereby made more uniform and gradual.

a screw. It requires no great effort of imagination, now that we have reached this point, to assume that the hydraulic ram or screw produces the pull on the test bar, while the movement of the weight along the lever gives us a method of measuring the load so produced.

There are two principal types of machine used for testing

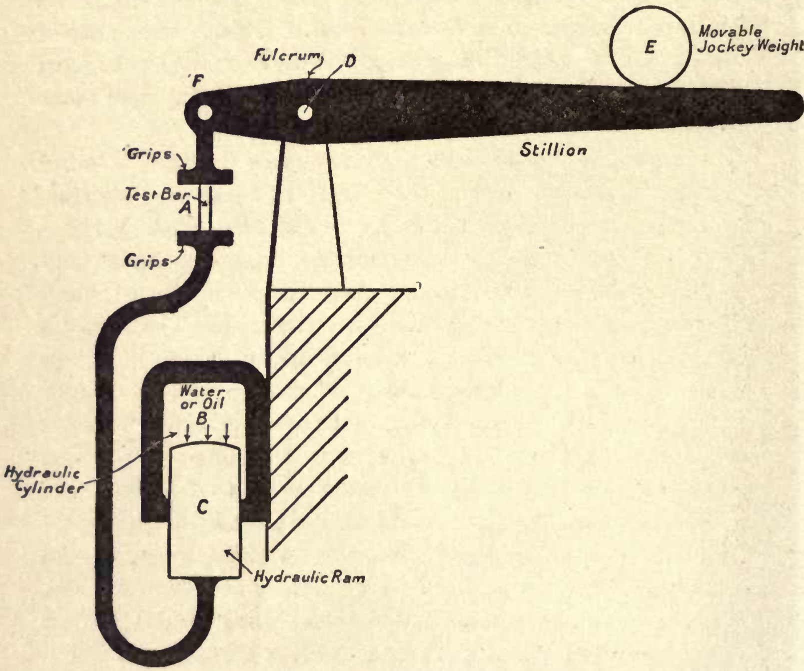


Fig. 2.—Diagrammatic Sketch of Vertical Type Testing Machine.

materials in tension, compression, or bending. They are termed vertical or horizontal machines, according as the specimen or test bar is placed in a vertical or horizontal position. A diagrammatic sketch of a vertical testing machine is shown in Fig. 2. The specimen or test bar A is held in a vertical position by means of grips, a detailed description of which will be given later. The load is applied by means of a hydraulic ram C, which works in a cylinder B. Water or oil

under great pressure is forced into the cylinder B and causes the ram C to move downwards. This tendency, however, is repressed by the specimen A, the tenacity of which opposes the load. Owing to the friction of the cup leathers, which are employed to prevent the water and oil from leaking past the ram, the pressure of the oil or water in the cylinder does not give us a true measure of the load on the specimen. The upper end of A is accordingly fastened by means of similar grips to the shorter arm F of a lever whose fulcrum is fixed at D. On applying the load, the downward tendency of F is counterbalanced by running the movable jockey-weight E along the longer arm of the lever (usually called the "stillion"). The length of the "stillion" is usually so calibrated that from the position of the weight along this arm we can at once read off the load on the specimen.

The horizontal type of tester is shown in Fig. 3. In principle it is precisely the same as the vertical machine, only the arrangement of the details being different. Here the specimen A is supported in a horizontal position and the load applied as

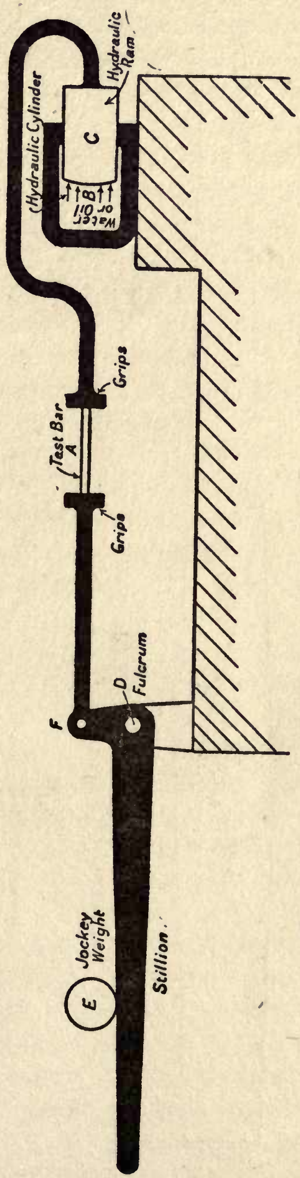


FIG. 3.—Diagrammatic Sketch of Horizontal Type Testing Machine.

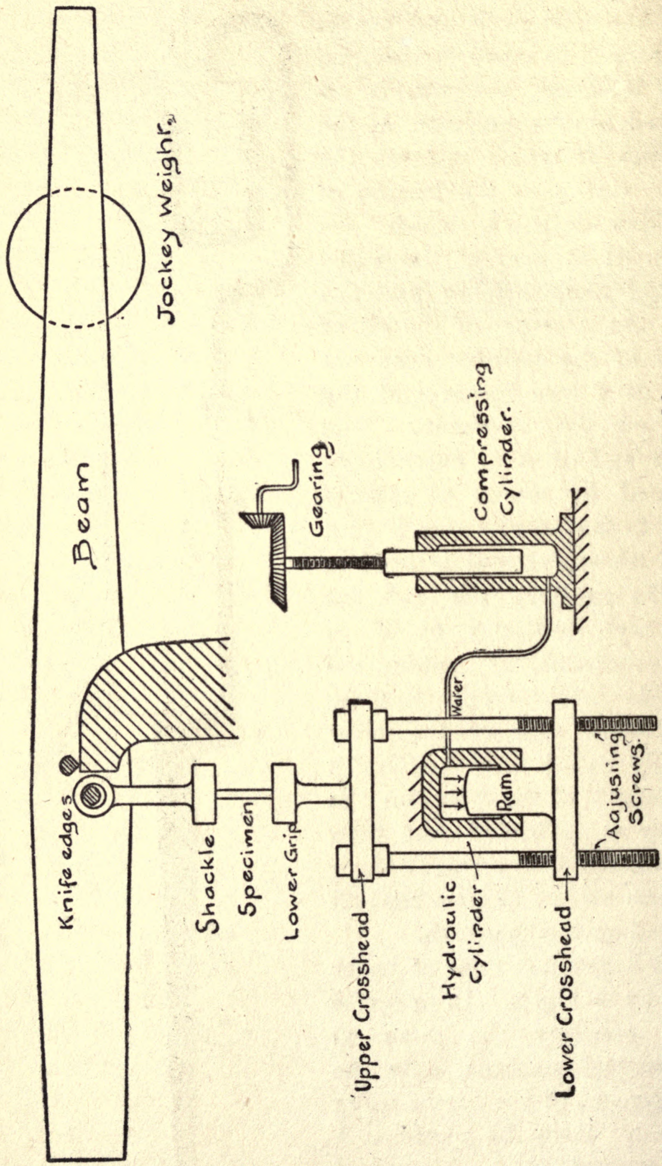


FIG. 4.—The Wicksteed Testing Machine.

before by a hydraulic cylinder B and ram C. The lever in this case, however, instead of being straight, is in the form of a "bell crank," as it is now desired to balance the horizontal pull on the specimen by the vertical action of the weight E.

Wicksteed Testing Machine.—We now pass on to consider some of the more important, and at the same time more complicated, machines used for testing the strength of the stronger materials (such as iron, steel, timber, etc.), in tension, compression, and bending. One machine can, as a rule, be adapted to test all these properties of a material, though, of course, the grips used and the kinds of specimen employed differ in each case. The principles upon which the Wicksteed machine works are indicated in Fig. 4. Water or oil is first admitted into the compressing cylinder. This consists of a hydraulic cylinder whose ram is moved backwards and forwards by means of a screw. It may thus be described as a screw-driven pump, in which the water attains a very high pressure (2,000 to 3,000 lbs. per square inch). This water under pressure is then admitted through a valve into the hydraulic cylinder, which is usually secured in an inverted position to the base of the main frame of the machine, so that, to all intents and purposes, it forms an integral part of the latter. Here it acts downwards on the ram, the pressure being transmitted through the lower crosshead to the adjusting screws, and thence to the upper crosshead which carries the lower grip for the test piece, and usually slides on some part of the framework of the machine. The upper grip is connected by means of a shackle to the beam through a knife edge. The beam itself usually consists of two wrought-iron plates kept apart by brackets at intervals, though sometimes it is made of cast-iron, which gives greater rigidity. Between the plates two steel cylinders are fixed, having grooves into which the hardened steel knife edges fit. On one of these the beam rests, the knife edge in that case being downwards. On the other is hung the upper shackle which supports the test piece. The jockey weight is usually moved along the beam by

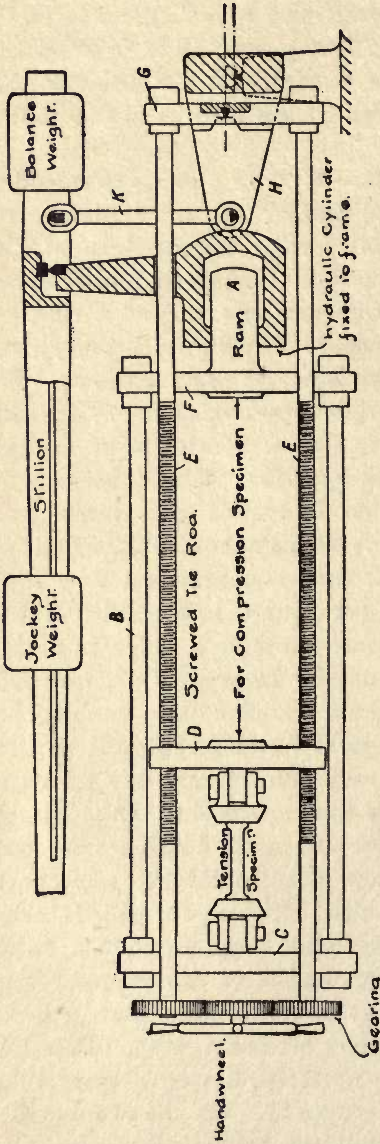


FIG. 5.—Sir Alexander Kennedy's Testing Machine.

means of a screw which traverses the whole length of the beam. The weight also carries a vernier which moves along a scale fixed to the beam, so that the position of the weight on the beam can be observed with great exactitude. The centre of gravity of the jockey weight is arranged to be as nearly as possible in an exact line joining the two knife edges, as if this were not so the effect would be that of a bent lever, and the leverage would alter slightly as the beam tilted up or down. The motion of the beam in this direction is, however, limited by stops at the free end.

The object of the adjusting screws is to enable the distance between the grips to be altered to suit the length of the specimen to be tested. The machine is here shown fitted up for a tensile test. If, however, a compression test is required, the lower grip is replaced by a square plate. A similar plate is fixed at some distance below this and is connected to the same point on the beam as the upper

shackle in the tensile test. Consequently, what was the lower shackle in the latter test is now the upper one, and *vice versâ*. If now the cylindrical test piece is placed between these two plates, the direction of stress will be in the reverse direction, and consequently the material will be compressed. The compression is transmitted to the beam in the same way as before

The Kennedy Machine (Fig. 5).—This is a well-known testing machine of the horizontal type. The ram of the hydraulic cylinder A is connected to a cast-iron sliding frame B, which carries an adjustable crosshead C in which are fixed the grips for receiving one end of the test bar. The other crosshead D is fixed between two screwed bars E which traverse the whole length of the machine, one above and one below the hydraulic cylinder. If a tensile test is to be performed the specimen is gripped between these two crossheads. To adjust the distance between them the key which fastens the movable crosshead C to the sliding frame is drawn out, the crosshead moved to the required distance, and the key then replaced. The frame has keyways cut in it at intervals of about 4 inches to allow this crosshead to be fixed in any position. For compression tests a flat plate is provided at that end (F) of the sliding frame which is nearest to the ram, and a similar plate on the fixed crosshead D, the specimen being gripped between them. The screwed rods which transmit the stresses to the levers are thus always in tension, the sliding frame being similarly invariably in compression. The tension is transmitted from the rods to a back crosshead G, which, through knife-edges, actuates two side levers H. The power being applied to these levers at a point above the fulcrum gives the effect of a bell-crank lever, so that the direction of the forces is changed from horizontal to vertical. This is invariably the case with horizontal testing machines, as we wish to balance the forces by means of a sliding weight, the direction of whose action is, of course, vertical. The outer ends of these side levers are connected by means of tension rods K to the short arm of the beam, the forces being measured by running out a jockey weight in the usual way.

The following are the dimensions of a 50-ton Kennedy machine:—

Diameter of ram, 16·15 inches.

Maximum jockey weight, ½ ton.

Arms of bell-crank lever, 3 inches and 24 inches.

Arms of beam, 8 inches and 100 inches.

∴ Total leverage of machine $=\frac{3}{24}\times\frac{8}{100}=\frac{1}{100}$.

∴ Capacity of machine = 50 tons.

Since the scale is 100 inches long, every 2 inches of travel represents an increment in loading of 1 ton. The sliding weight is, however, composed of cast-iron discs which are removable, so that for smaller powers greater accuracy can be obtained. The accumulator, which supplies the hydraulic

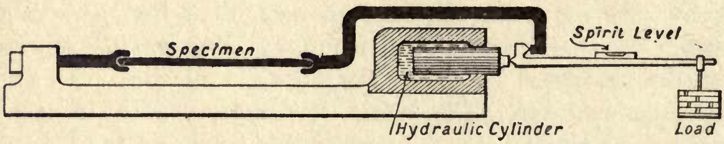


FIG. 6.—Diagrammatic Outline showing Principle of Werder Machine.

cylinder, is capable of giving a pressure of 2,000 lbs. per square inch. It is fed by three throw pumps, 1½ inches in diameter with 3-inch stroke. These are driven through gearing by a three-phase electric motor running at 880 revolutions per minute. These figures are given with the intention of conveying to the reader some idea of the actual size of the principal details and auxiliary apparatus of a machine of this capacity.

The Werder Machine.—Although not used, except in a modified form, in England, one of the most convenient and accurate machines is that devised by Werder. Fig. 6 indicates the general scheme of mechanism employed, the action of which is obvious. It will be seen that by this arrangement of levers it is possible to place the whole of the controlling gear at one end. Hence, specimens of any desired length can be tested merely by extending the frame. The usual length

for which these machines are built is 30 feet. Arrangements are made by which specimens can be tested up to this length in both tension and compression. Machines on this pattern have been built for the Government testing laboratories at Berlin and Munich, for the polytechnic schools at Zurich and Vienna, and for several manufactories and railways. It was on a machine of this type that most of the famous researches of Bauschinger were carried out.

It should be clearly understood that the diagrammatic scheme illustrated in Fig. 6 is only intended to illustrate the general principle employed. For details of the methods employed for utilising this principle in actual practice, the student should refer to the original treatise (in the German language) given below.[1]

300-ton Machine.—The Civil Engineering Department of the University of Birmingham has the privilege of possessing a very large testing machine. It was desired to carry out work

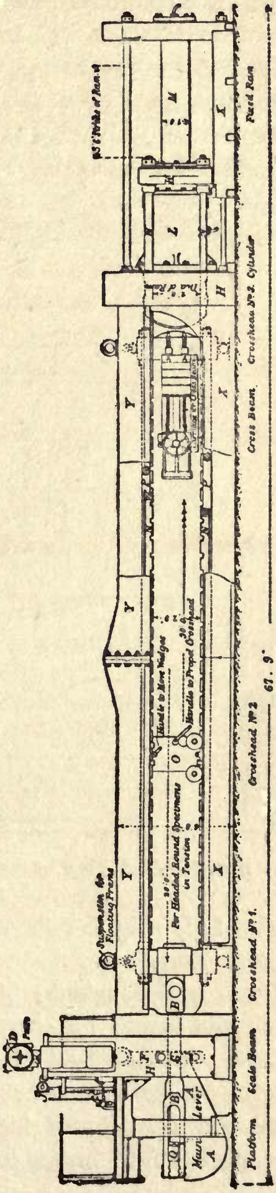


FIG. 7.—Side Elevation of 300-ton Testing Machine in Birmingham University.

[1] *Mittheilungen a. d. Mechanisch technischen Laboratorium in München.* Heft 1 und 3. *Maschine zum Prüfen der Festigkeit der Materialien und Instrumente zum Messen der Gestaltsveränderung der Probekörper.* München, 1882.

on actual structures. The smallest capacity of a machine for this class of work was fixed at 300 tons. There was some difficulty in preparing a specification for such a large size machine. Eventually Messrs. W. and T. Avery, Ltd., Soho Foundry, Birmingham, were commissioned to prepare and submit designs for such a machine, and a machine of 700,000 lbs. capacity was finally constructed by them and installed in the laboratory.

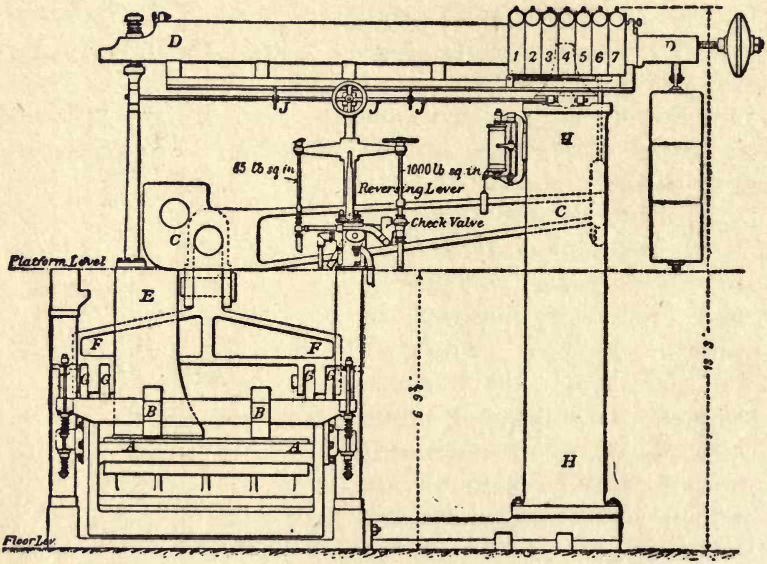


FIG. 8.—End View of 300-ton Birmingham Testing Machine.

The following details will give the reader an idea of the general design:—

Leading dimensions: Maximum length for tension, 28 feet; maximum length for compression, 30 feet; span for bending, 20 feet. The over-all dimensions of the machine are: Total length, 67 feet 9 inches; maximum height, 13 feet 3 inches; width varying from 7 feet to 21 feet. The wedge-grips can take specimens $3\frac{3}{4}$ inches in diameter, or 6 inches by $2\frac{1}{2}$ inches flat.

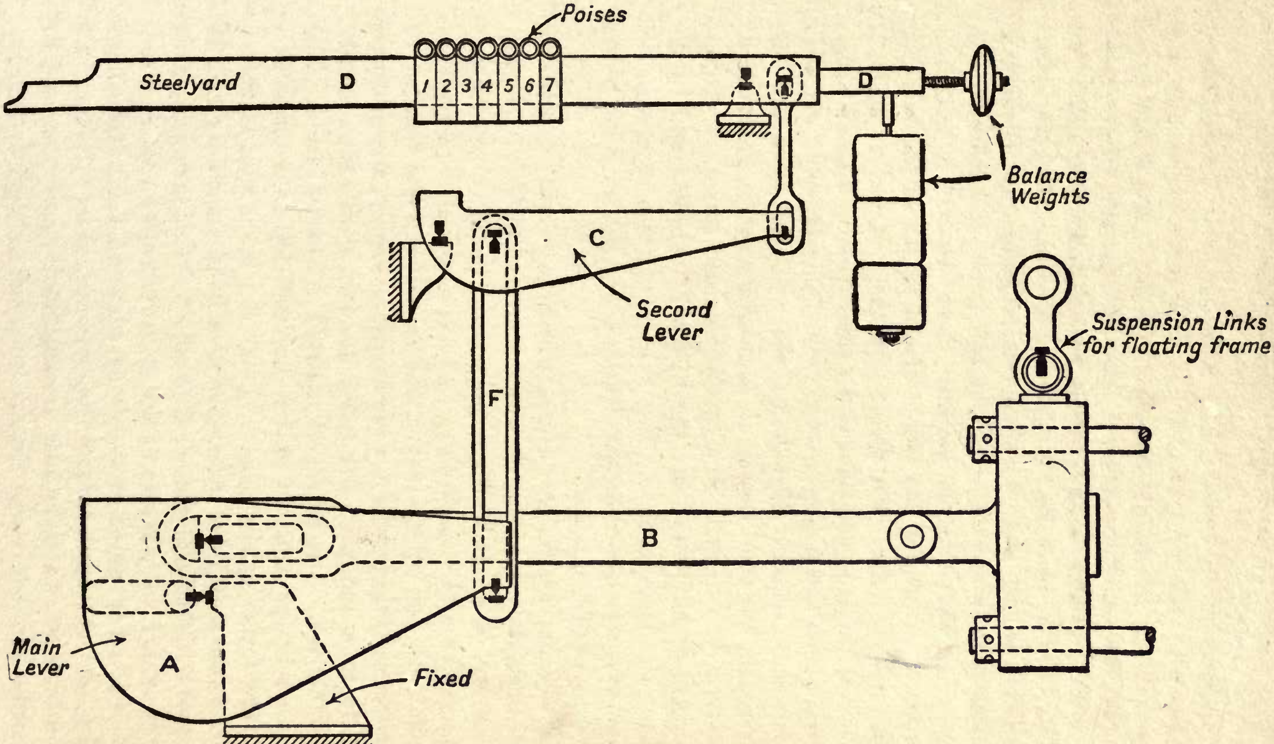


FIG. 9.—Details of Poise Gear and Levers on Birmingham 300-ton Machine.

General arrangement: The machine is of the horizontal type, with the ram at one end and the lever system and operating platform at the other. Figs. 7 and 8, on pages 25 and 26, show the general arrangement, the former being a front elevation, and the latter an end elevation. In Fig. 7 the massive cast-iron bed X X of the machine is terminated at each end by a rigid vertical standard. The tops of the standards are connected by two horizontal columns Y Y, spanning the distance between them without intermediate support. Thus, for the whole of the length of the machine occupied by a specimen under test, there is a clear space of 2 feet 9 inches at the sides and a clear space of 3 feet 9 inches visible from the platform on the top. The latter is not only important because it enables the operator to watch the specimen, but also because it enables heavy specimens to be lowered into the machine by the overhead traveller. To one vertical standard is fixed the hydraulic cylinder, and to the other the lever system. Fig 9, on p. 27, is a diagrammatic view of the steelyard mechanism, and Fig. 10, on p. 29, of the main and return rams.

Straining mechanism: The machine is operated by hydraulic pressure, two supplies of water being available: the town pressure, of about 100 lbs. per square inch, for preliminary operations and adjustment; and the accumulator supply, of 1,000 lbs. per square inch. The ram L is 2 feet 8 inches in diameter, giving, with the low-pressure supply, a total thrust of 35 tons, and with the 1,000 lbs. per square inch the full 700,000 lbs. The stroke of the ram is 5 feet 6 inches. The main cylinder is bolted to the standard, and thus forms part of the frame of the machine, and the main ram is hollow and forms a cylinder moving over a fixed subsidiary ram M 1 foot 8 inches in diameter. The object of this arrangement is to provide for the return of the main ram after a test. Water from the low pressure supply is admitted behind the fixed ram, and the main ram is driven back into its cylinder. To the head of the main ram are fixed four racks N sliding in grooves in the frame of the machine, and notched throughout

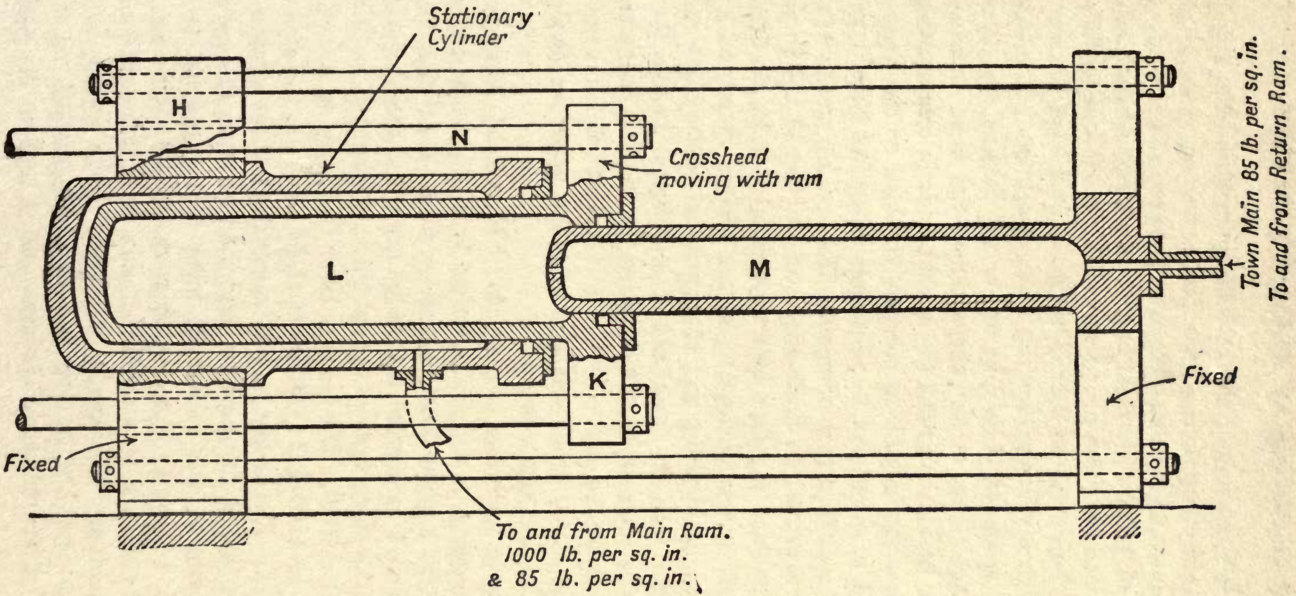


FIG. 10.—Details of Main Ram on Birmingham 300-ton Machine.

their length to permit of the travelling crosshead No. 2 being keyed to them in any desired position, according to the length of the specimen under test. The travelling crosshead is moved by means of gearing, terminating in a handle at each side. Thus the load on the ram is transmitted to the sliding racks, thence to the crosshead 2 fixed to them, and from the crosshead through a spherical seating to the specimen. The other end of the specimen is held by one of the floating crossheads 1 and 3, according to the character of the test. Between crosshead 2 and crosshead 3 the specimen is in compression; or if the bending beam is in position, the load on the beam is transmitted to crosshead 3. Between crosshead 2 and crosshead 1 the specimen is in tension. The floating crossheads 1 and 3 are suspended on knife-edges on the top of the frame, and are connected together by four tension rods P, the whole arrangement forming a floating frame. When crosshead 3 is in use—*i.e.*, in bending and compression tests—these rods transmit the load to crosshead 1, and hence to the lever system. The connecting link between the floating frame and lever system is the main link B B, terminating in a steel bearing-block Q Q, which engages with the upper knife-edge of the first or bell-crank lever.

Weighing or recording mechanism: This consists of a main bell-crank lever A A, with its principal knife-edge, 5 feet long, engaging with a plate fitted in a recess in the bed. The load is brought on to a similar knife-edge (forming with the main knife-edge the short vertical arm of the bell-crank) directly by the main link B B. The second lever C C, Fig. 8, and the final lever or steelyard D D run at right angles to the axis of the machine. The former has its fulcrum on a short column E fixed to the bed of the machine, and the load from the end of the long arm of the bell-crank lever is transmitted to it through side links G G and a cross-shackle F. The steelyard has its fulcrum on a special column H on the right hand of the machine. The steelyard carries seven poises, each of which at the end of its run represents 100,000 lbs. on the specimen. Thus, whatever the total load, 1 inch on the steel-

yard scale always represents the same increment of load. At the same time, there are no loose weights to put on or take off. The poises can be made to slide over or back along the steelyard by hand, or they may be put into gear with a screw, and moved by hand-wheels J.

The machine is operated from a raised platform at the steelyard end; the supply and exhaust pipes are brought to an operating valve on this platform, and the load can be taken on or off, the steelyard balanced and the load recorded by a single operator on this platform, who is also able to see the specimen under test. It would have been a great loss to the equipment had this unique machine been omitted. The great amount of research work possible with it is obvious to every engineer.

The author is indebted to Professors Stephen Dixon and F. H. Hummel for the above particulars and drawings, and to the editor of *Engineering* for the photograph of the machine given in the frontispiece.

Avery Testing Machine.—The following specification of a 100-ton machine is supplied by this firm and describes its construction in great detail. A novel feature is the adoption of double acting in the hydraulic cylinder, the other points being very similar to those of the Kennedy machine. This is included as an example of how such a specification should be drawn up as well as with the object of familiarising the reader with the principles of design adopted by this firm.

Specification of Horizontal Testing Machine.

To test specimens in tension, compression, bending and shearing.

Maximum testing capacity	100 tons.
Longest specimen in tension	12 feet.
Longest specimen in compression	15 feet.
Longest beam for transverse test	15 feet.

This machine is designed specially for the testing up to 100 tons strain of full-size members to destruction. It consists generally of a hydraulic cylinder and ram having a stroke of 3 feet 6 inches, forming the straining portion, and a system of compound levers forming the weighing or recording portion. The hydraulic supply is derived from the town main supply.

The straining portion of the machine consists of a heavy section double-acting hydraulic cylinder of special design. The main cylinder, which is a heavy casting, has a large hollow ram which slides over a smaller stationary ram.

The working pressure may vary from 850 lbs. to 1,120 lbs. per square inch and the diameter of the larger ram is of such dimensions that the tester will give 100 tons strain with the minimum pressure. The cylinder is accurately bored, and the rams are both turned. The cylinder is provided with the usual hydraulic leathers, secured in position by a turned and faced cast-iron cover bolted to the cylinder flange.

The main ram is fitted into a massive cast-steel head, into which the turned and screwed ends of the straining racks are secured by means of turned and screwed nuts. These straining racks are four in number, and are of mild steel and run the whole length of the bed. They are for the greater part of their length rectangular in section, terminating in round ends where they pass through the ram head. Machined slots are provided at intervals of 9 inches to receive the main crosshead. Four nuts are screwed on to the straining racks where they pass through the cylinder flange, and these allow of the ram being locked at any position of its stroke, allowing specimens to be placed under a strain for an extended period.

The main ram is copper-plated to prevent corrosion.

The hydraulic cylinder is turned outside and fitted in a heavy casting, which is bored to receive it. This casting stands upon the ground, and to it are bolted the four cast-iron columns in which the straining racks slide. These columns are planed between the castings supporting the hydraulic cylinder and the casting against which the pull upon the main lever fulcrum is received. They each have a machined groove or slot to act as guides to the straining racks, and their ends are all faced.

A substantial cast-steel crosshead runs upon wheels, and is arranged to be capable of being placed in any position in the straining racks; machined slots are provided at the top and bottom of the crosshead into which loose keys are inserted to connect the same to the straining racks. This crosshead is made hollow to receive on the one side the special holders for the tension test and on the other side the adjustable plattens for testing columns in compression.

The holders for the tension test are inserted at the back of the cross-head and have spherical seatings to give true alignment to the specimens. These holders will allow of any of the recognised forms of specimen being tested. Headed specimens are secured in split collars, while other types of specimens are secured in hardened steel wedge grips.

The plattens for testing columns are also provided with spherical seatings.

The weighing or indicating portion consists of a very heavily-constructed main lever, the sides of which are mild steel plates. Hardened steel knife-edges are fitted into these plates, and these backed by means of machined mild steel blocks acting as distance pieces. The knife-edges

are of the best quality steel hardened, and are arranged to be 1 inch in length for every 5 tons of strain.

The bearings are all of hardened steel, the fulcrum bearing being fitted into a cast-iron pedestal on the main casting. The weight of the lever is supported by means of wrought-iron links, with hardened steel bearings, from a cast-iron cross-beam resting upon short columns which are bolted down to the cast-iron base plate.

The main knife-edges of the levers bear in a hardened steel bearing-block contained in a projecting verge which is bolted to a massive cross-head secured to the main tension rods. Two other crossheads are attached to these rods, and the whole floating frame of three crossheads and two tension-rods are suspended from cast-iron pedestals upon the main frame by means of wrought-iron links having hardened steel bearings.

The steelyard is a massive iron casting, fitted with hardened steel knife-edges arranged to be 1 inch in length for every 5 tons of strain. Its fulcrum knife-edge rests upon a hardened steel bearing fitted into a cast-iron pedestal bolted down to the main column.

The steelyard is traversed by three poises, which are connected or disconnected at will to a central screw.

When tests below 25 tons are required the first poise is used independently of the other two and gives readings from zero up to 25 tons, the 1-ton mark being 8 inches apart and the sub-divisions being $\frac{1}{1000}$ of a ton. For tests between 25 and 50 tons the first and second poises are coupled together, and these now give readings from zero up to 50 tons, the 1-ton marks being 4 inches apart, the sub-divisions being $\frac{1}{1000}$ of a ton. For tests between and 50 and 100 tons all three poises are coupled together, and readings from zero up to 100 tons are obtained, the 1-ton marks being 2 inches apart, and the sub-divisions in this case being $\frac{1}{1000}$ of a ton. All the finer sub-divisions are obtained by means of verniers upon the poises.

The poises are propelled by a hand-wheel at the front of the tester, this being connected by means of gearing to the central screw.

This arrangement of poises secures that neither of the poises need to be removed from the steelyard.

A carrier and buffer spring are provided to lessen the shock upon the steelyard when the specimen breaks.

The steelyard is connected to the main lever by means of wrought-iron links having hardened steel bearings.

Tension test.—Seven pairs of hardened steel wedge grips are supplied with the machine to enable flat and round specimens to be tested in tension. The maximum length of specimen in tension is 12 feet, and this specimen can be tested without the removal of the cross-beam.

Compression test.—Columns up to 15 feet in length and of a maximum section of 12 inches diameter can be tested without removing the cross-beam used in the bending test.

Bending or transverse test.—This test is made by means of a heavy steel cross-girder, consisting of rolled steel joists having steel plates riveted to their flanges. A cast-iron grooved track is bolted to the plates of the cross-girder, and this is traversed by two pedestals, each containing a hardened steel hemi-cylindrical bearing block. These pedestals can be quickly adjusted to any desired span to a maximum of 15 feet, by the movement of hand-wheels at the ends of the cross-girder.

A presser foot which has two hemi-cylindrical bearing blocks is fitted into the movable crosshead in place of the platten for the compression test, and this bears centrally on the beam being tested.

The cross-beam is arranged to be easily removed. To facilitate this a carriage, running free upon wheels and having side rollers, is provided. To centralise the beam, projecting pieces upon it are allowed to clip at each side of a projecting boss upon the end crosshead.

Shearing test.—This apparatus consists of two cast-iron portions which are guided and slide in one another. One portion is bolted to the casting at the front of the steel cross-beam, and to this the specimen is clamped by means of cross-plates and set pins.

The other casting envelops the specimen, against which it is forced by means of the straining crosshead of the machine.

Both portions of the shearing apparatus are provided with hardened steel tools to give the shear. The whole apparatus is strongly constructed and well finished.

An absolutely pure shearing test is given by means of this apparatus.[1]

The general design of the machine is arranged to give easy access to the ram head for the removal of the hydraulic leather packing.

The straining racks are always in tension and are secured from deflection due to their own weights by the insertion of machined strips. The floating frame is suspended by means of links having hardened steel bearings.

Amsler Testing Machine (Fig. 11).—This machine differs from any that we have hitherto mentioned in the fact that no beam or weight is used to measure the load on the specimen. Great care is taken in machining the cylinder A and its ram, to ensure a perfect fit between the two, so that no cup leather, or other packing, is necessary to prevent leakage. The friction at this point being eliminated, the pressure inside the cylinder may be taken as a measure of the load on the test bar. Oil is forced from the compressing cylinder B into the hydraulic

[1] This statement, made by the makers, must be understood to mean pure shear as far as it is possible to obtain it without the very special means described in the section on compound stress.

cylinder A, where it does work on the specimen. The pressure from A is transmitted by means of a pipe D to the cylinder C. As this pressure is necessarily very high, no mercury column of convenient height can be utilised at this point to record it. Accordingly it is made to act on the ram E which actuates the plunger G. This combination forms a reducer (which is exactly the opposite of an intensifier), for, since the rod and plunger E and G are in equilibrium, it follows that the total

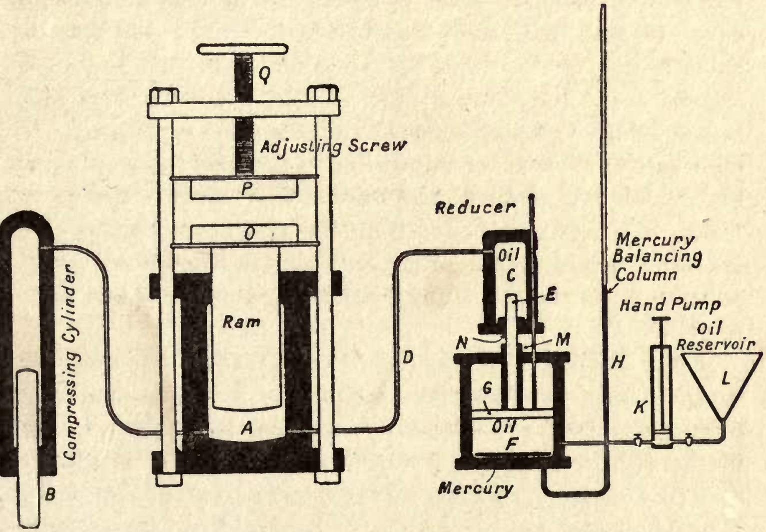


FIG. 11.—Amsler Testing Machine for Short Compression Specimens.

downward pressure on E is equal to the total upward pressure on G. Now, since G is much larger than E, the pressure per square inch on G must therefore be much less than that on E; in fact, the pressures per square inch in C and F will be inversely as the areas of E and G. The plunger G presses downwards on a layer of oil, the pressure of which is balanced by that of a column of mercury H, which is calibrated to read directly the load on the specimen.

In some cases, however, the maximum power of the machine is not required, so that greater accuracy in reading the loads on the specimen is desirable. The ratio of reduction is then

made less by the following device: Oil is pumped into the chamber F by means of the hand pump K from the reservoir L. In this way the plunger G is raised until the sleeve M comes into contact with the ring N and raises it off its seating. The oil in C is now pressing not only on the ram E, but also on the annulus N, which surrounds it, thus enlarging the effective area of E. This, of course, has the effect of raising the total load on the top piston and, consequently, that on the bottom one G. Thus the pressure in F is more nearly equal to that in C than was before the case; the mercury column H is made longer, and thus more sensitive to the rise in pressure in the main cylinder A. In fact, the arrangement is equivalent to an enlargement of the scale of loading. To eliminate friction as far as possible in the reducer, the plunger and piston are given a backward and forward rotation by means of linkwork actuated from the main compressor. The specimen to be tested is placed between the two tables O and P, adjustment for length being effected by the screw and hand-wheel Q.

Riehlé Testing Machine (Fig. 12).—In the Riehlé machine we again revert to the jockey weight and lever as a method of measuring the force exerted on the test bar. The loading mechanism in this case, however, consists, not of a cylinder and ram, as in previous machines, but of two strong screws D and E, which pass vertically up the machine. These screws are rotated (through gearing which permits of several speeds being used) by an electric motor, and pass freely through the bed of the frame. The specimen A is held by clips to the framework B and the table C. The latter is moved either upwards or downwards by rotating the screws D and E, on which it fits like a nut.

The whole of the framework B rests on a system of levers to which the load on the specimen is transmitted through knife-edges at F and G. The final balance is effected by the jockey weight H, which moves on the graduated stillion arm K. It can easily be shown that the pull P in the connecting rod M L does not depend on the relative loads on F and G,

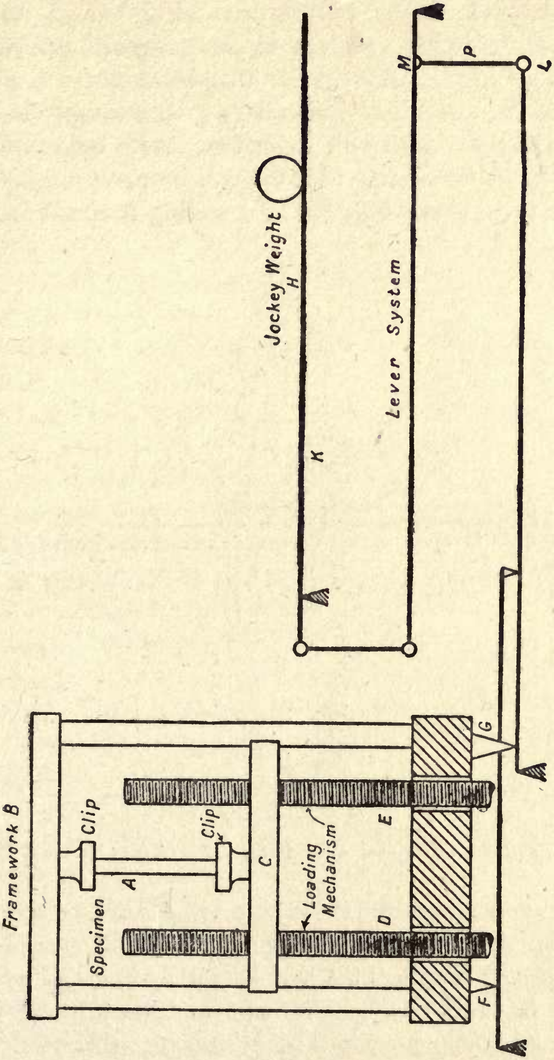


FIG. 12.—Riehlé Testing Machine.

but merely on the total load on the knife-edges. Consequently, if the specimen is unsymmetrically placed in the grips, the accuracy of the machine will not be affected.

In machines of this type as actually built there are several

special features. Placed between the main driving pulley and the vertical screws is a system of change gears, controlled by three levers and a hand-wheel. One lever works the reverse while each of the other controllers give two speeds, and by varying the combination of these four levers we can get eight speeds forward or reverse (*i.e.*, tension or compression). The top speed is generally only used for setting the machine. For

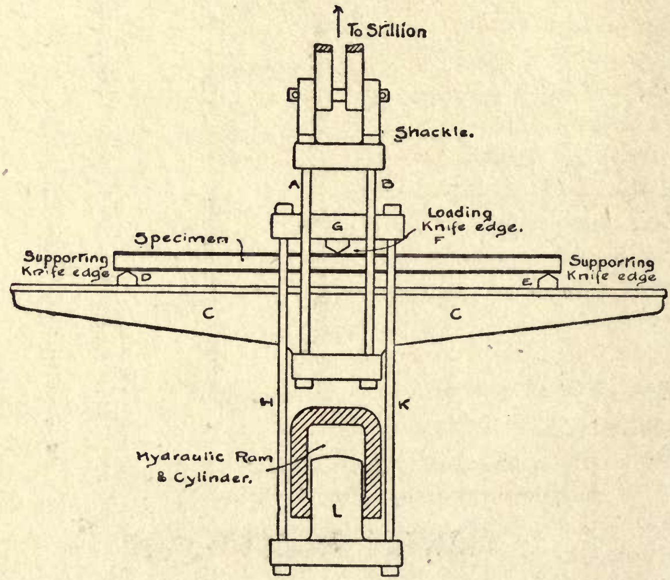


FIG. 13.—General Arrangement for Girder Testing.

rapid commercial testing it is also desirable to fit change speed pulleys on the driving shaft, or use a variable speed motor. By this means the machine can be set or changed over from a tension test to a compression test in a few minutes without any manual labour on the part of the experimenter. These machines are almost invariably fitted with autographic apparatus, and the whole can be made entirely automatic by the means described on page 42. One excellent feature of this type of machine is that, as the experimenter stands at the levers, specimen, poise reading, autographic diagram, and all

the controlling levers can be seen or regulated without moving his position. It may be added that, since to develop the full advantages of this machine the whole is run as fast as possible, there is, of course, a liability for an inexperienced experimenter to smash some of the gears by changing speed carelessly. In fact, considerable experience is necessary to manipulate everything in the best possible manner. It is sometimes urged against this type of multilever machine that wear and friction are likely to cause greater inaccuracies than in single lever machines.

Arrangement of Machines for Bending Tests.—All the machines hitherto described can be used for tension, compression, or bending tests. Fig. 13 shows the arrangement of a vertical testing machine for testing girders, etc., in bending. Connected with the stillion knife-edge by means of four tie rods A and B, is a table C, with a flat machined face. Two knife-edges D and E are bolted to this table in such a way that their distance apart can be adjusted to suit any size of specimen within the limits of the machine. These knife-edges often rest on spherical seats, which adjust themselves as the load is applied, so that the supporting forces are exactly vertical in direction. The specimen to be tested rests symmetrically across these knife-edges, and is loaded at the centre by means of a knife-edge F.

The ram L is forced downwards by the water in the hydraulic cylinder, and the load transmitted by means of tension bars H and K to the knife-edge F.

Horizontal machines can be adapted to take specimens for bending in a similar manner. They are not, however, so convenient for testing large specimens as the vertical type of machine, as in the latter the girder rests by its own weight on the supporting knife-edges, while in the horizontal machine it has to be supported in position by the central load.

Bailey Transverse Testing Machine.—A simple machine for testing the transverse strength of a beam is that made by W. H. Bailey & Co., Ltd., which has a capacity of 40 cwt. The load is applied, as in the case of ordinary testing machines,

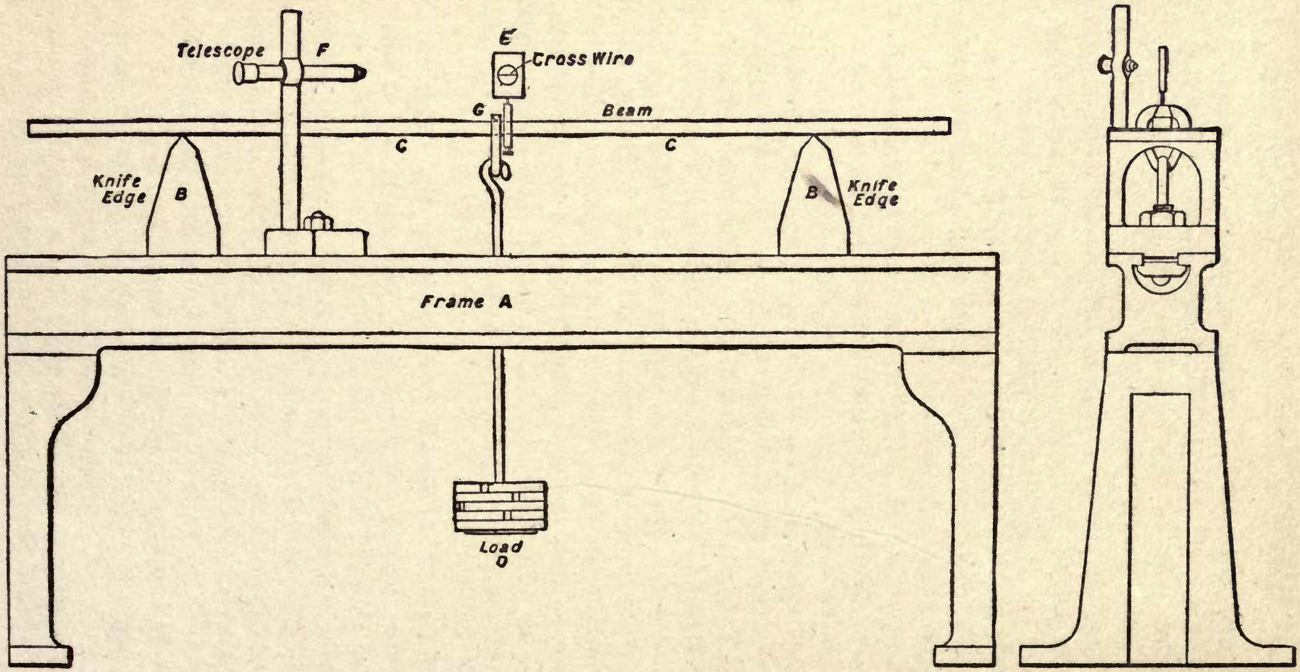


FIG. 14.—Apparatus for Testing Deflections of Beams.

by means of a lever and sliding weight. The test bar is supported at the ends in two blocks, which have knife-edges pointing downwards as the load is applied in an upward direction. The load is applied through a knife-edge at the centre of the specimen, and is produced by sliding the jockey-weight along a graduated lever. The lever itself is counterpoised, as in the case of other testing machines, so that it is only the sliding weight which loads the test bar. As the specimen bends, the lever is prevented from assuming an inclined position by means of a screw and hand-wheel, which take up the movement of the bar. In making these tests it is obvious that the bars must be accurately placed and the load applied centrally.

Keep's Testing Machine.—This is used to test small bars about $\frac{1}{2}$ inch in thickness, and from the tests so made the quality of cast-iron is determined. It is constructed to trace a diagram of the behaviour of the bar while under test. The load is applied in a similar manner to the Bailey machine, but the lever is not kept floating, being allowed to go down with the bending of the bar. A pencil arm is attached to the centre of the bar and a sheet of paper placed in the holder behind it. The movement of the bar is magnified five times, so that the actual deflection is more easily measured. The paper holder is moved in a horizontal position as the jockey weight moves along the lever, the two being connected together by means of cords. In this way a curve of deflection against load is obtained for each specimen, and the behaviour of the bar under transverse loading is thus automatically recorded.

The Deflection of Beams.—The apparatus shown in Fig. 14 is for the purpose of directly measuring the deflection of small beams under a given loading. The frame A carries two knife-edges B B, whose distance apart is adjustable to suit beams of different lengths. These knife-edges support the beam C which is to be tested by applying a load D through a knife-edge at G. The beam also carries at this point a frame and cross-wire E, the position of which can be observed with great accuracy by means of a telescope F. The load is applied by

adding weights at D, and the deflection for each load observed by noting the movement of the cross-wire at E against a suitably graduated scale. In this way the accuracy of the laws for theoretically determining the deflection of a beam can be experimentally checked by means of the very simple apparatus just described. In some cases the cross-wire is placed inside the telescope, and a scale graduated to $\frac{1}{100}$ of an inch is fixed vertically to the centre of the beam, a reading being taken after the application of each load. The beam may also be fixed as a cantilever by bringing the two knife-edges closely together and rigidly gripping the end of the beam between them. An old lathe bed can be used for the framework of the apparatus.

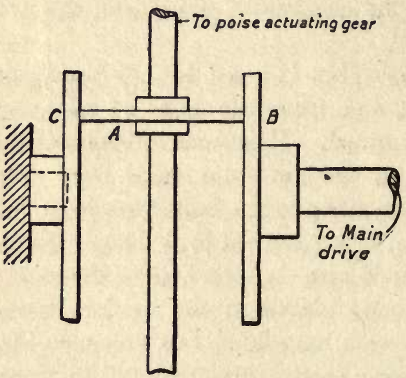


FIG. 15.—Change Speed Mechanism in Poise Gear of Riehlé Testing Machine.

Automatic Testing Machines.—The general principle underlying machines fitted with some appliance for automatically keeping the poise balanced is as follows:—

The load is applied at a constant rate in the case of screw machines, such as the Riehlé, by driving the screws at a constant speed, or in the case of hydraulic machines, such as the Wicksteed, by applying pressure at a constant rate to the hydraulic cylinder.

The poise weight is likewise run along the beam at a speed which is adjusted to such a value as to tend to run out at a slightly faster rate than is necessary to keep the machine balanced. At some point in the driving mechanism of this latter arrangement is an electric clutch, which is put in or out of gear according as a contact worked by the movement of the poise arm is made or broken.

Thus, in the arrangement sometimes fitted to the Riehlé machines, an electric contact is arranged so that when the beam rises it makes contact, actuates the clutch, and drives the weight along the beam until balance is restored, when the circuit is broken and the poise weight remains stationary until the increase in the load again raises the beam and starts the poise driving-gear again. This latter mechanism is driven by the same source of power as that which drives the screw gear for applying the load. The relative speed of the load-applying gear and the poise-controlling mechanism can be varied by means of the three-disc mechanism shown in Fig. 15. The disc B is driven at constant speed, while the disc A can be moved by hand along its shaft and thus vary the relative speed of A and B. It is desirable to adjust this velocity so as to keep the arm balanced as near as possible, independent of the electric control, as otherwise the contact makes and breaks in rapid succession, and as the circuit is of necessity highly inductive, violent arcing takes place, especially if the current is supplied from the lighting mains through a suitable resistance, as is sometimes done. In any case, a certain amount of trouble is generally experienced from this latter cause, and some skill is required in order to reduce it as much as possible.

It will be observed that the mechanism shown in Fig. 15 is reversible, and consequently as soon as the maximum load is reached it is desirable to put this over to a fairly high speed of reverse and actuate the clutch mechanism by hand. No doubt even this latter could be controlled electrically by placing a contact on the bottom stop and changing over from one stop to the other at the same time as the mechanism of Fig. 15 is reversed, but such is not usually done, and the time between maximum load and breaking load is usually very short, and an experienced operator generally prefers to control this portion himself.

A very fine example of an automatic testing machine is that installed in the Northampton Polytechnic Institute, built

by Messrs. J. Buckton & Co., of Leeds, to the requirements of Mr. C. E. Larard.[1]

In this machine the poise weight is driven by a separate electric motor, the speed of which can be varied over a wide range by an adjustable field resistance. The motor drives the poise through an electric clutch, but differs from the Riehlé control, inasmuch as the fall of the beam does not break the circuit, but short circuits the clutch coils, an arrangement which prevents a great deal of the destructive arcing previously mentioned. A novel and important addition is likewise made by which the instant the clutch is short circuited a brake is applied to the driving shaft, thereby preventing any over-running of the poise weight. This clutch is held off by means of an electro-magnet, which is released simultaneously with the clutch. The straining motion is applied by hydraulic power from an accumulator, and the speed can consequently be adjusted to a nicety by the control valve. It is stated that in practice it is found that the speed of straining and working the poise weight can be so relatively adjusted as to be almost independent of the electric control.

An important addition to this particular machine is the provision whereby the poise weight can be made either 1,000 or 2,000 lbs., and a further load can be added at the end of the beam, increasing the maximum load to 150,000 lbs., while another special attachment enables torsion loads of 400,000 inch-lbs. twisting moment to be carried out on short specimens.

Shackles.—The design of the grips for holding the specimen in the testing machine is a very important point. They should be designed to give as nearly as possible a perfectly axial stress. If the pull is not central, bending of the specimen will result, and the strength obtained by experiment will not be the true tensile or compressive strength of the material. The wedge principle is mostly employed for tension shackles, to prevent the specimen from slipping when the load is applied.

[1] See paper in Proc. Inst. Mech. Eng., July, 1907.

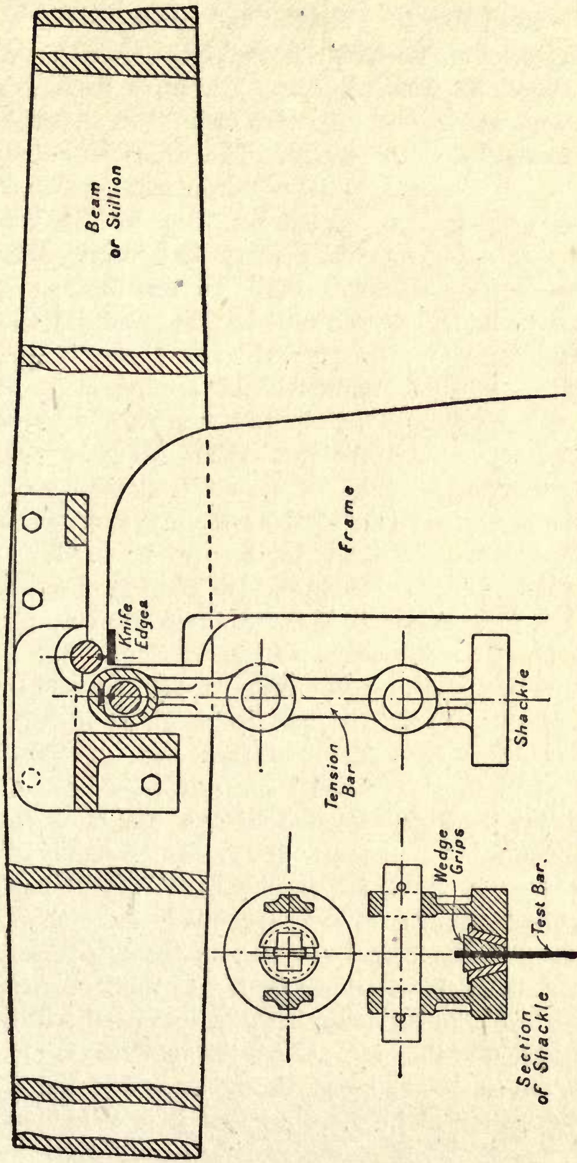


FIG. 16.—Details of Knife-Edges, Shackle, and Grip.

The principle of these is exemplified by the "Wicksteed" grips, shown in Fig. 16. The flat test bar is gripped between two wedge grips which have serrated faces, like a file, to prevent the specimen from slipping. The grips themselves rest in a seating, whose inner sides are inclined to the same angle as the outer sides of the wedge. The whole is secured in a round cast-iron plate, which is fixed by tension bars to the beam on which the jockey weight slides. It will readily be seen that, the greater the pull on the specimen, the more firmly will the grips wedge themselves in the seating, and the more tightly will they hold the specimen. Another type of specimen is enlarged to form an eye at each end. Pins are passed through the hole at each end to secure it to the forked shackle. In this way the test piece is free to move in one plane to ensure axial loading. The method most often used, however, enables the test bar to move in any direction, so that bending the bar is almost an impossibility. This is effected by the use of a spherical seat. If the bar is merely cast and not machined, it may be made with spherical or ball ends. The grips, which are each made in two parts, have spherical seatings on them, between which the ball ends of the specimen rest. As the load is applied, these seatings allow the test bar to adjust itself with its axis in the direction of the pull. When the specimen is machined, the ends are usually enlarged, the inside end of the enlarged part being spherical in shape, so that it is self-adjusting in the clips; or the ends of the specimen can be screwed and fitted in hemispherical seats as shown in Fig. 17.

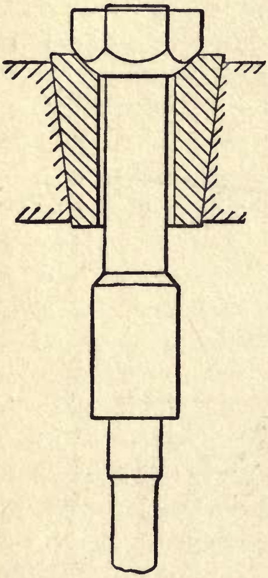


FIG. 17.—Ball Seating for Tension Specimens with Screwed Ends.

Compression Shackles are easier to design, merely consisting in most cases of two flat parallel plates between which the accurately faced ends of the cylindrical test piece are gripped as the load comes on. In some cases, especially where long specimens are used, one of these plates is formed with a spherical back, which adjusts itself in parallel with the other.

Where great accuracy is required, as in research work, it is necessary to use seatings which shall ensure, as far as possible, central loading. Figs. 18 and 19 show two methods of loading ordinary compression specimens. The method shown in Fig. 20 has been tried by the author, and found entirely unsuccessful. Fig. 21 illustrates the method employed by Prof. Lilley in loading hollow struts during some of his classic experiments, mention of which will be found in the bibliography.

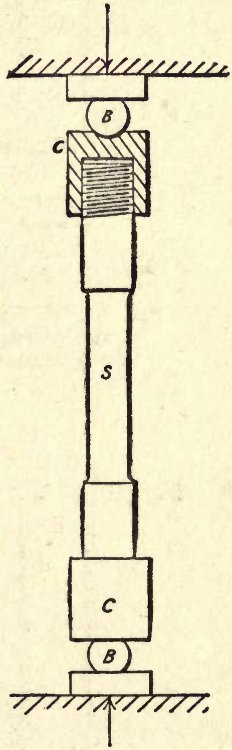


FIG. 18.—Ball Seating for Specimen in Compression.

Calibration of Vertical Machines of the Wicksteed Type.—Machines of this type can be readily tested for accuracy in the following manner. *To test for wear of knife-edge and to estimate width of edge:*—

(1) Open out the shackle heads to the maximum distance apart as if for a compression test.

(2) Carefully ascertain if any parts of the shackles which move relatively to one another are in contact, as the friction produced by this means may be considerable.

(3) When everything is free, set the beam indicator so as to be right over one side of the slot, and then get beam in equilibrium with the beam end near the top stop.

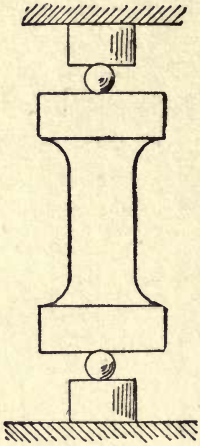


Fig. 19.—Method of Loading Compression Specimen.

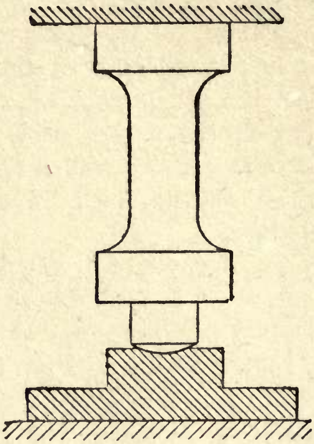


Fig. 20.—Unsuccessful Method of Loading Compression Specimen.

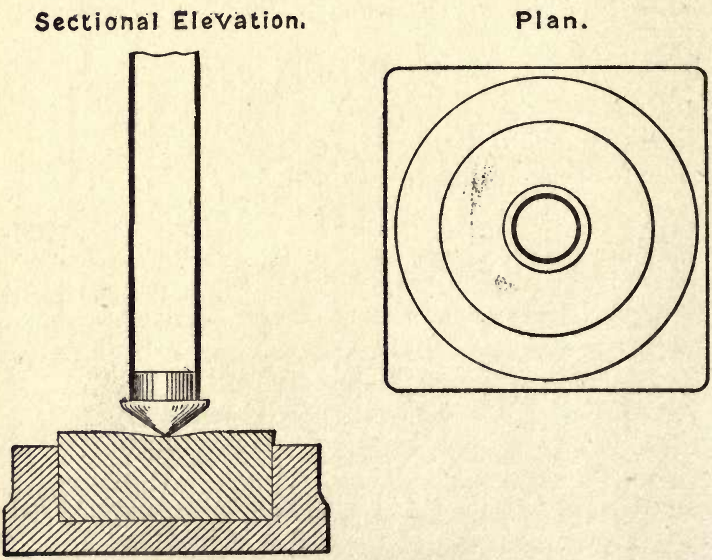


Fig. 21.—Prof. Lilley's Method of Testing Hollow Struts.

(4) When all is balanced set vernier accurately to zero, and again adjust for equilibrium if necessary.

(5) Add weights to the lower shackle up to half a ton or more. In this connection it will be found convenient to first put on the cross-beam used in beam tests, as in a 50-ton Wicksteed, this weighs over 400 lbs., besides making a convenient support for the other weights.

(6) Again restore equilibrium and note reading on scale.

(7) Shift the beam indicator over to other end of slot, set

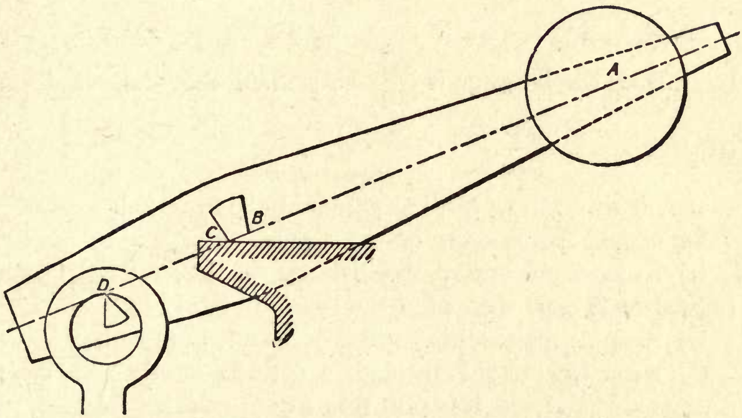


FIG. 22.—Diagram showing Effect of Wear of Knife-Edge in Machines of the Wicksteed Type.

for equilibrium with beam nearly on bottom stop; note reading.

(8) Remove load; adjust to equilibrium; note reading.

It will be seen that we thus obtain—

(*a*) True load on shackle.

(*b*) Reading of machine with beam up.

(*c*) Reading of machine with beam down.

Record of Calibration Test.—In a certain test on a 50-ton Wicksteed machine the following results were obtained :—

(*a*) 1485·6 lbs. = ·663 tons; (*b*) ·657 tons; (*c*) ·660 tons. The mean of (*b*) and (*c*) = ·6585.

$$\text{Hence percentage error at low loads} = \frac{\cdot 663 - \cdot 6585}{\cdot 663} \times 100$$
$$= \cdot 68\% \text{ low.}$$

The percentage error would probably be much less at higher load.

The difference in reading with the beam up and the beam down is due to the width of the knife-edge.

The correct distance of the knife-edge D from the fulcrum is 3 inches, hence the width CB is of the nature

$$\frac{\cdot 660 - \cdot 657}{\cdot 6685} \times 3'' = \frac{\cdot 003}{\cdot 6685} \times 3'' = \cdot 013''.$$

Exaggerating the width as in Fig 22, we see that when the beam is up the leverage is $\frac{AC}{CD}$, and when the beam is down the leverage is $\frac{AB}{BD}$.

This is as small as can be reasonably be expected.

To Check the Weight of the Balance-weight.—

(*a*) Hang some known weight, say 56 lbs., on the longitudinal scale near the end of the beam.

(*b*) Balance the machine and adjust vernier to zero.

(*c*) Move the weight through a definite number of scale divisions (preferable 40) and again balance the machine.

(*d*) Note how far the balance-weight has been moved.

In a certain test on the same machine as above when the 56-lbs. weight was moved through 40 divisions (from 50 tons to 10 tons) the balance-weight was moved as near 1 division as could be read on the machine. Since moving 56 lbs. through 40 divisions is equivalent to moving 1 ton through 1 division, the balance-weight was certainly within ·1 per cent of 1 ton.

CHAPTER IV

STRAIN-MEASURING INSTRUMENTS

Whenever a body is subjected to a load, or stress of any kind, some strain or deformation of shape is sure to result. If this strain occurs in finished structures, it may have inconvenient or even dangerous results, so that we desire to know the actual effect produced by stressing a material to a certain degree in changing its shape. Moreover, if we can find out the separate effect of each increment of load, the stress strain curve drawn from such readings may give us some useful information about the material that we propose to use. The most usual case is that of tension. Let us assume, then, that we are about to test a bar of the material in question, with a tensile load between certain limits. The immediate effect of the application of this load will be to stretch the bar by an amount which varies with the intensity of the load. We wish to measure the amount of this stretching, which is, after all, very small in proportion to the length of the bar. The easiest way, of course, is to centre-punch the bar at a point near each end, and measure the distance between them with a pair of dividers after the application of each increment in the load. Another method would be to screw two collars to the test bar, at a distance apart, fixed by the length of a standard rod. As the bar began to stretch, a wedge gauge could be introduced into the space between the end of the standard rod and the bottom collar, the extension thus being measured with very fair accuracy. But these methods are quite inadequate to measure the very small extensions which take place at stresses below the elastic limit of the specimen. These it is most valuable for us to know, as it is only at stresses below the elastic limit that any material can be used. For the purpose of measuring these

minute extensions, some form of "extensometer" must be used. In these instruments the stretching of the specimen is magnified either by mechanical or optical means, until the slightest extension can be measured with an accuracy ranging from $\frac{1}{10000}$ of an inch in the former case to $\frac{1}{1000000}$ of an inch in some forms of optical instruments.

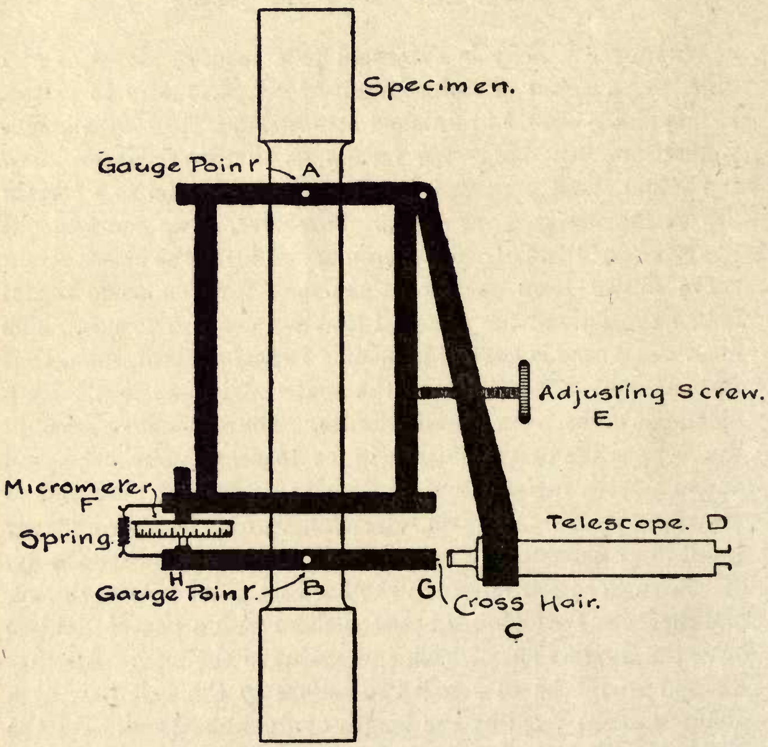


FIG. 23.—Ewing's Extensometer.

Ewing's Extensometer.—A diagram of this instrument is shown in Fig. 23. The framework of this extensometer, which is indicated by thick black lines in the diagram, is secured to the specimen by screws at A and B. The distance between them, generally called the gauge length, is usually eight inches. As the test bar stretches, the distance A B becomes greater, and

as the end H is fixed in position relative to the frame, it will readily be seen that the movement of G will be double that of B. The movement of G is observed by the passage of a cross hair C along a graduated scale in the eye-piece of the telescope D, which is capable of adjustment by means of the screw E.

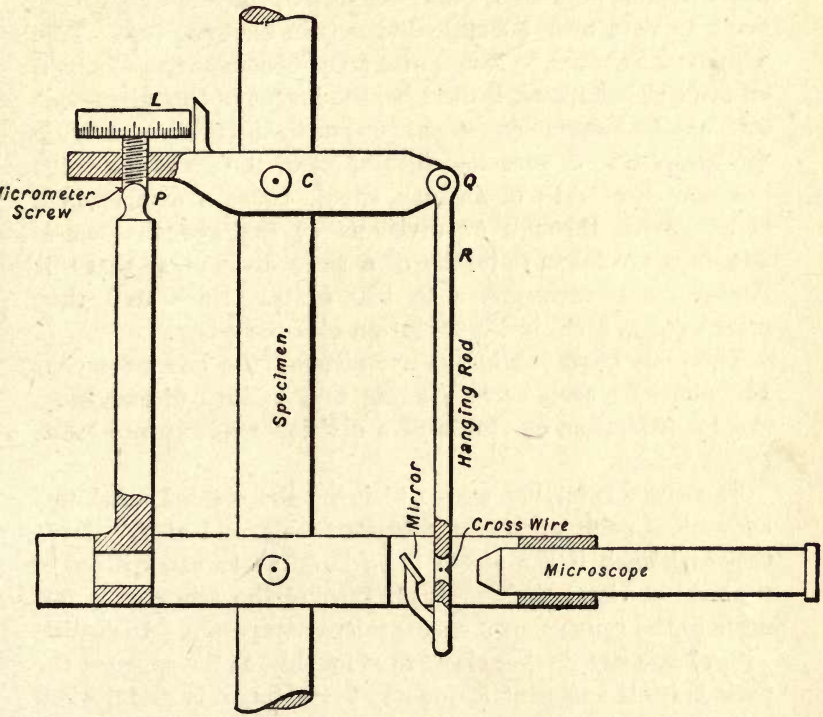


FIG. 24.—Diagrammatic Outline of Latest Type Ewing's Extensometer.

The graduated scale is calibrated by means of the micrometer screw F, which is turned through a known distance, and the movement of C observed. The actual value of each scale division can thus be obtained in a very simple manner, the accuracy being about $\frac{1}{50000}$ of an inch.

In the latest type of this important instrument some modifications have been made in the general arrangement, although not in the principle. Fig. 24 shows this latest form.

The object sighted is one side of a wire stretched horizontally across a hole in the bar R and illuminated by a small mirror behind. The distances C P and C Q are in this instance equal, with the effect that the movement of the sighted mark is double the extension of the rod. The length of the microscope is adjusted so that one turn of the screw causes the mark to pass over 50 scale divisions in the eye-piece. This adjustment should be tested with an extensometer as mounted on the specimen, and, if need be, the length of the microscope tube can be altered by drawing out or in the portion carrying the eye-piece. A complete revolution of the screw L, which has a pitch of $\frac{1}{50}$th of an inch, should cause a displacement of the mark through 50 divisions of the eye-piece scale. Readings are taken to tenths of a scale division, so that this displacement corresponds to 500 units. Each unit then means $\frac{1}{50000}$ inch, in the extension of a test-piece.

The scale engraved in the eye-piece of the microscope has 140 divisions each corresponding to $\frac{1}{5000}$ inch of extension, and by estimation of tenths of a division readings are taken to $\frac{1}{50000}$ inch.

The screw L further serves to bring the sighted mark to a convenient point on the micrometer scale, and also to bring the mark back if the strain is so large as to carry it out of the field of view; thus, a single turn of the screw adds 500 units to the range shown on the micrometer scale. In dealing with elastic strains there is no need for this, as the range of the scale is itself sufficient to include them, but it is useful when observations are being made on the behaviour of metals as the elastic limit is passed.

In other forms of this instrument the micrometer is dispensed with, the position of the telescope relative to the frame being fixed. The scale in the eye-piece of the telescope is then so graduated that its divisions represent some definite fraction of an inch.

Unwin's Extensometer.—In Prof. Unwin's instrument, shown in Fig. 25, two tee-brackets are fixed to the specimen a gauge length apart. To each of these brackets a spirit level

is attached, so that they can always be kept exactly in a horizontal position. To the lower bracket, in addition, is clamped the measuring pillar C, which carries within it a fine screw D, with a micrometer head E. This screw has

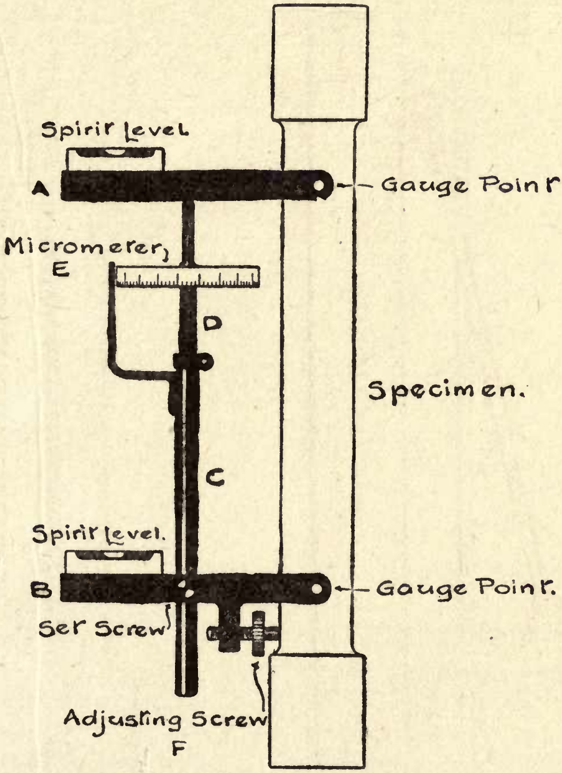


FIG. 25.—Unwin's Extensometer.

50 threads per inch, and, since the micrometer has 200 divisions, an accuracy of $\frac{1}{10000}$ of an inch is obtainable.

When about to take a reading the lower bracket is first levelled by the adjusting screw F, and then the upper bracket is levelled by the micrometer. The difference between this micrometer reading and the previous one gives us the change in length of the specimen.

Marten's Extensometer.—Fig. 26 is a diagrammatic sketch of Marten's instrument. An arm A with a point at its lower end is clamped to the specimen by elastic bands or springs at B and C. Between the top end and the specimen there is a

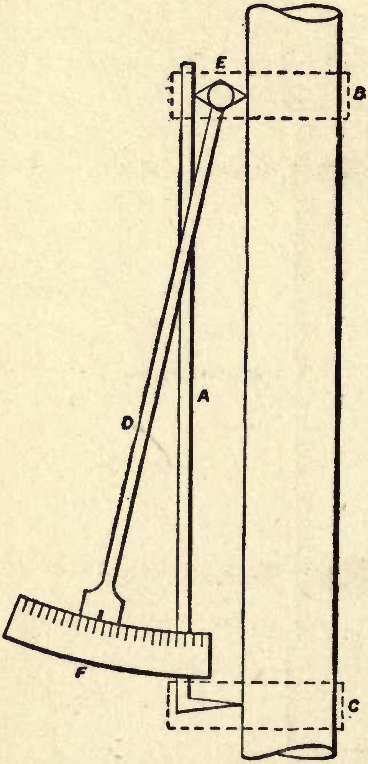


FIG. 26.—Marten's Pointer Extensometer.

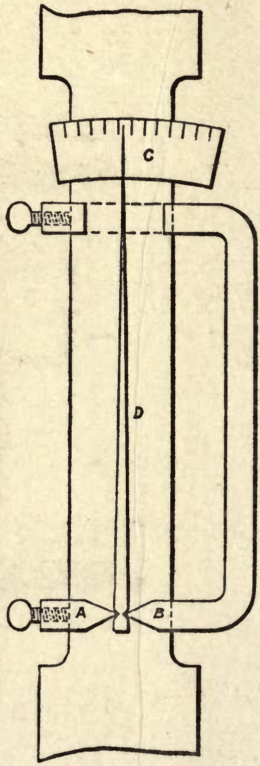


FIG. 27.—Ashcroft's Extensometer.

small diamond-shaped lever E. Any movement of A relative to the specimen, such as is caused by an extension, tilts the piece E, thus moving a long pointer D over a fixed scale F. When the magnification is 50, readings can be conveniently taken to $\frac{1}{500}$ mm.

Ashcroft's Extensometer.—An instrument described by Ashcroft is shown in Fig. 27.

The upper end of the knife-edge B is rigidly connected to the upper end of the specimen whilst A is clamped to the lower. A and B fit into small notches in the lever D, and consequently a greatly magnified movement of the relative

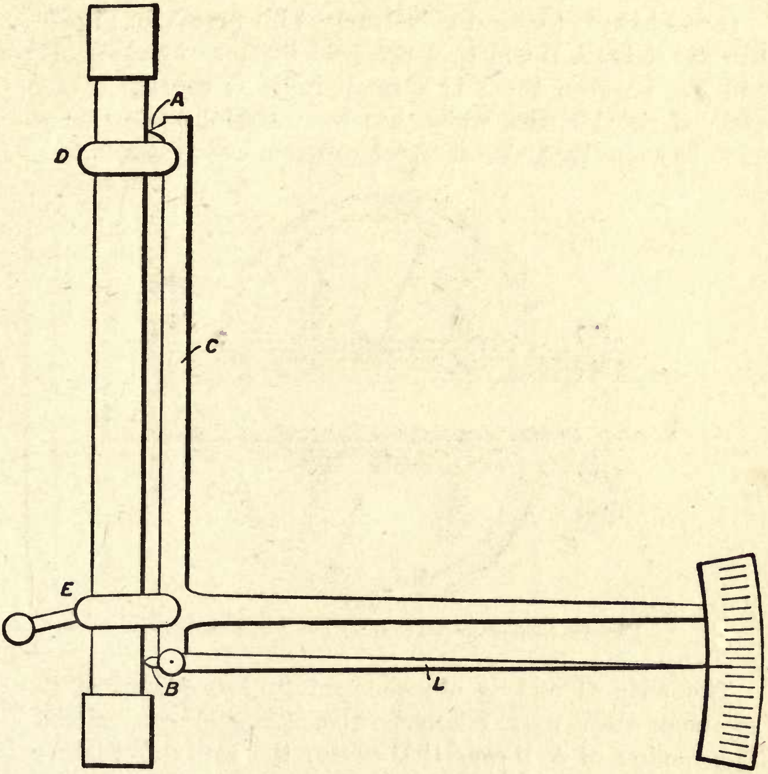


FIG. 28.—Kennedy's Extensometer.

motion of A and B is shown by a pointer D on a fixed scale C.

Kennedy's Extensometer.—This is almost identical in principle with that of Martens. Fig. 28 shows the instrument in outline, and is practically self-explanatory. Reading can be taken to the nearest $\frac{1}{10000}$ or $\frac{1}{20000}$ inch.

Stromeyer's Rolling Pin Type Strain Indicator.—This type

of instrument is shown diagrammatically in Fig. 29 adapted for the measurement of strains in testing-machine specimens. A modified form, but involving the same principle, has been largely used for the measurement of strains in finished structures such as bridges.

It will be seen that in the instrument illustrated in Fig. 29 two flat strips A B and C D are held together by springs E and F. Between them is a small roller G consisting of a piece of circular wire which has been carefully prepared so as to be as nearly an exact circular section as is possible.

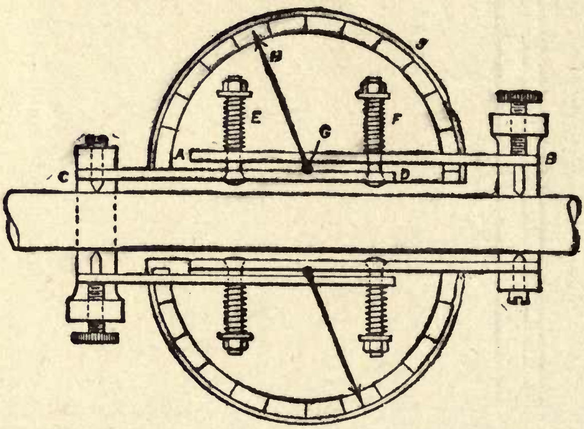


Fig. 29.—Stromeyer's Rolling Pin Extensometer.

The ends C and B are clamped to two points of the specimen which move relatively when the specimen extends. The motion of A B over C D causes the roller G to turn, which movement is read by observing the movement of a pointer H over a fixed scale J. Results have been obtained in which each scale division represents $\frac{1}{10000}$ inch, and a further estimation could be made. In the design of instrument used on existing structures, shown in Fig. 30, A is the roller moving between a fixed plate C and a moving one B.

B is connected to the upper gauge clamp by a piece of annealed wire F of the same material as the structure. F is kept tight by means of a spring E. The gauge length is

between the screws H H and G G. The rolling pins are made of hardened cast-steel. They are attached to light straw pointers by means of paper envelopes and sealing wax. The papers are cut after fixing, so that the pointer is balanced. These rolling pin pointers can easily be renewed or re-fixed with a warmed pair of pincers, and this is generally necessary when sudden strains, which appear to act like blows, are recorded by the instruments. In such cases the straw pointers will generally break off. It is not advisable to replace them by wire pointers, for then even small but sudden strains have a powerful effect and loosen the rolling pin, which defect is not always noticeable and may lead to errors.

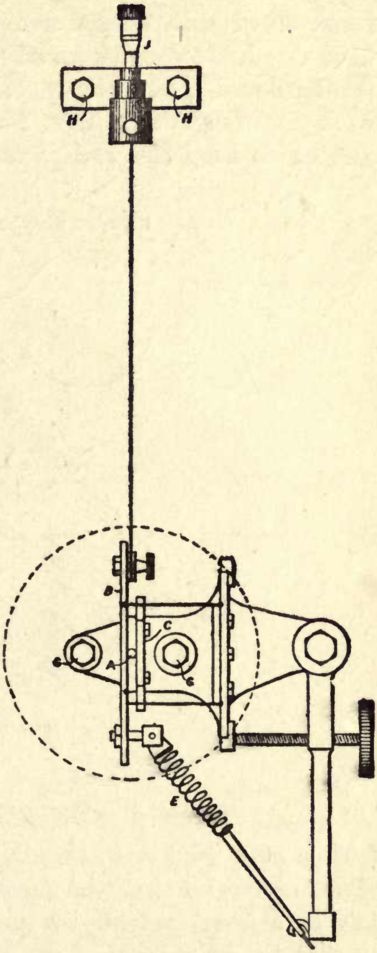


FIG. 30.—Stromeyer's Rolling Pin Type Extensometer (as used on finished structures).

The Cambridge Extensometer.—This instrument, the general scheme of which is shown in Fig. 31, consists of two separate parts, each of which is separately attached to the test-piece A by hard conical points. The steel rods carrying these points slide in geometric slides, and after being driven gently in centre punch marks at P and P^1 are clamped in position. Both parts of the instrument should

be capable of rotating quite freely about the points, but there must be no backlash. The lower piece carries a micrometer screw fitted with a hardened steel point B, and a divided head C. It also carries a vertical arm D, at the top of which is a hardened steel knife-edge. The upper and lower pieces work together about this knife-edge, the balance weight serving to keep the two parts in contact. A nickel-plated

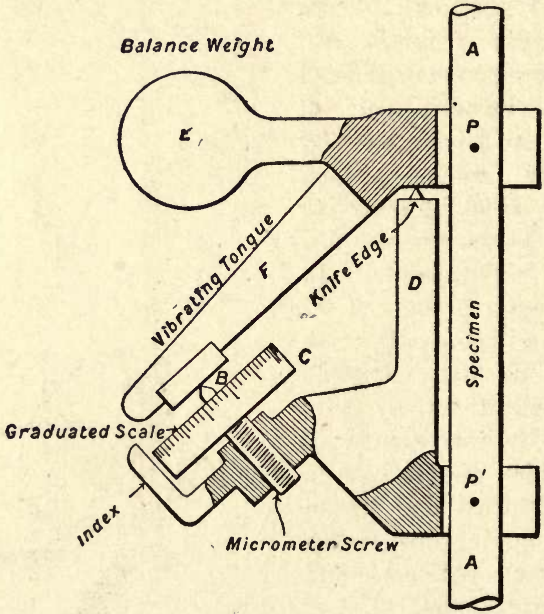


FIG. 31.—Cambridge Extensometer.

flexible steel tongue F, forming a continuation of the upper piece, is carried over the micrometer point B. This tongue acts as a lever, magnifying the extension of the specimen, so that the movement of the steel tongue to or away from the point B is five times the actual extension of the specimen. To take a reading the thin steel tongue F is caused to vibrate, and the divided head then turned till the point B just touches the hard steel knife-edge on the tongue as it vibrates to and fro. This has proved to be the most delicate method of setting the micrometer screw, as the noise produced and the

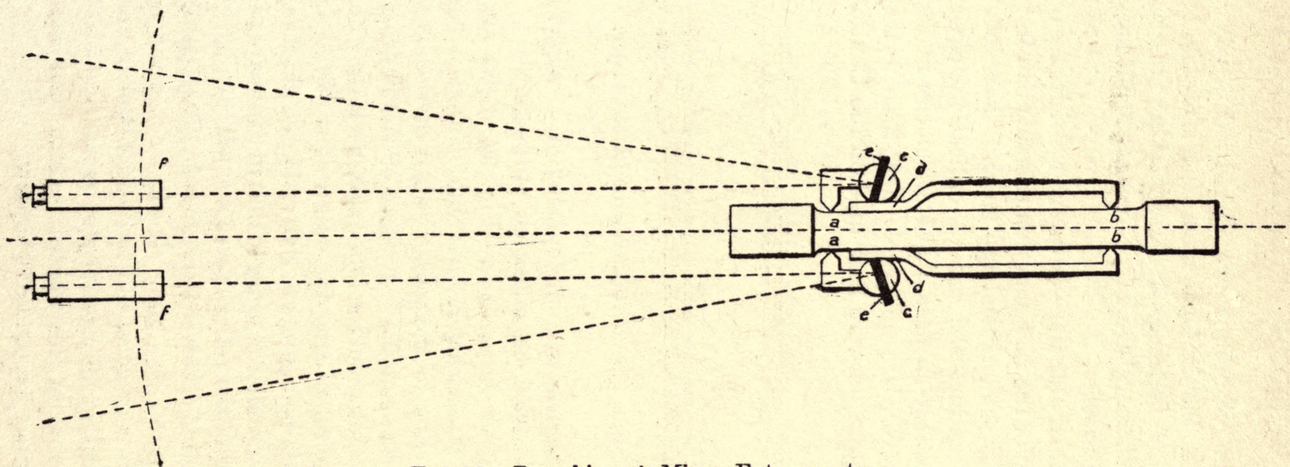


FIG. 32.—Bauschinger's Mirror Extensometer.

fact that the vibrations are quickly damped out indicate to $\frac{1}{1000}$ mm. the instant when the screw is touching the tongue. This instrument is, according to the National Physical Laboratory's report, reliable to about one-thousandth part of a millimetre.

Optical Instruments.—Greater sensitiveness than that given by any of the foregoing instruments can in general only be attained by some optical appliance. There has been rather a prejudice against the use of optical instruments in this country, probably on account of difficulties in focussing, etc. This is, however, less noticeable now than formerly. These optical instruments were first used on the Continent. Their

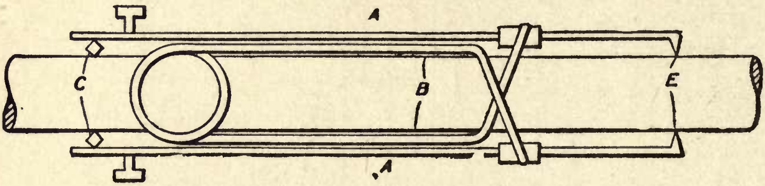


FIG. 33.—Marten's Mirror Extensometer.

great advantage is the employment of a weightless lever—a beam of light—for magnification purposes.

Bauschinger's Apparatus.—Fig. 32 shows an instrument designed by Bauschinger. *a a* and *b b* are the points held in by suitable clips to the gauge points of the specimen. The connection between the two parts of the instrument, one of which is fixed at *a* and the other at *b*, is a rolling one formed by a caoutchouc roller *c* moving over a light spring *d*. Hence, as the two gauge points move relative to one another, the roller *c* is turned in a similar manner to that in Stromeyer's instrument. The twisting of the roller moves a small mirror *e*, the angle of movement being observed by means of a telescope at *f*. Readings can be taken to $\frac{1}{10000}$ mm. It will be observed that readings are taken on both sides, and to Bauschinger belongs the credit of first realising the necessity of measuring strains in more than one plane, an idea which has since been extended by the author to three planes at 120° apart.

Marten's Mirror Extensometer.—In another form of optical instrument devised by Martens, the rollers used by Bauschinger are replaced by small diamond-shaped knife-edges. Figs. 33 and 34 illustrate this instrument. Like Bauschinger's instrument, it measures strains on two sides. A A are two flat plates having knife-edges at E. They are held together by springs B on each side, and press on knife-edges at C. Fig. 34 shows another view of the diamond pieces, and the method of carrying the mirrors. M is the mirror pivoted in the frame P by small set screws at N N. On the other side a set screw presses against the mirror, whose motion is resisted by a small spring D. This allows the inclination of the mirror to be adjusted. R is a weight to balance the mirror, and T a pointer which, when set in contact with the bar S, indicates that the knife-edge Q is correctly at right angles with the bar S.

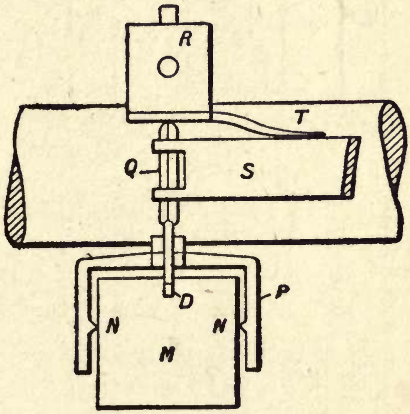


FIG. 34.—Detail of Mirror Attachment, Marten's Extensometer.

Morrow's Extensometer.—Yet another form of optical instrument is one devised by Dr. Morrow, which embodies the same principle as Marten's but is so arranged that the image of a scale held some distance away can be viewed in the mirror by means of a telescope. A second stationary mirror reflects the zero mark. This instrument is said to read to $\frac{1}{1200000}$ of an inch, having a magnification of about 3,000.

Stromeyer's Optical Extensometer.—An extensometer of great delicacy was designed by Mr. C. E. Stromeyer in the eighties, originally for the measurement of local strains in metal structures, but the particular design illustrated was

specially designed for measuring the cross contraction of test pieces in order to obtain a direct measurement of Poisson's Ratio.[1] It depends on the important principle of the interference of light.

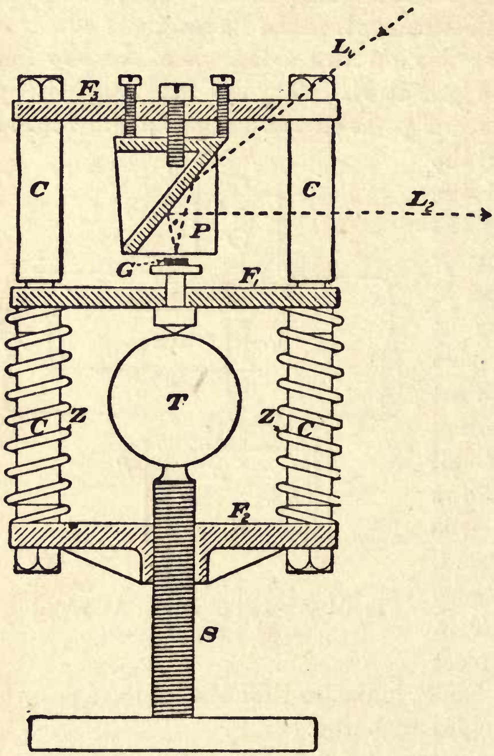


Fig. 35.—Stromeyer's Optical Extensometer.

If white light is projected on to a small piece of dark glass, the reflected ray can be considered as made up of two parts, one reflected from the outer surface and one from the back surface. Since one has travelled slightly farther than the other, the two rays will not be exactly in phase, the consequence being that they interfere and in the case of white light the reflected ray would be split up into coloured bands, while in the case of yellow sodium light, which is used with this instrument, alternate bands of dark and light are observed when the reflected ray is seen in a suitable form of telescope. If before being reflected by the dark glass the light suffers a previous reflection at another surface and the two reflecting surfaces are moved relative to one another, the dark interference bands will appear to move along the second surface past a line which can be scratched on the surface. The

[1] See p. 134.

distance apart of the interference bands can be calculated and also the relative movement of the two reflecting surfaces for a given movement of the bands past the fixed line.

Fig. 35 shows a diagrammatic sketch of the method used to carry out this principle in practice. T is the section of the test piece which is pressed against the point on the frame F by the screw S. G is the dark glass which, as soon as T contracts, is pulled away from the glass prism P by means of the four helical springs[1] Z Z which surround the columns C C and which are firmly secured to the frames F_2 F_3. The latter carry the adjustable glass prism P, which is so shaped that the ray of sodium light L_1 does not coincide with its reflected ray L_2.

The source of light was a sodium-tinted Bunsen flame, while L_2 was observed through a telescope. The inclination of the rays of light in the narrow space between the prism P and the dark glass G was carefully measured, and found to be 19°, so that each interference band, as seen in the reflected yellow light, ought to represent a distance of ·0000109 inches. That is to say, a relative movement of the two frames of this amount would cause a movement of the dark bands equal to their distance apart. Careful measurements with the fine screw S, however, showed the movement to represent ·0000120 inches, or 10 per cent. more.

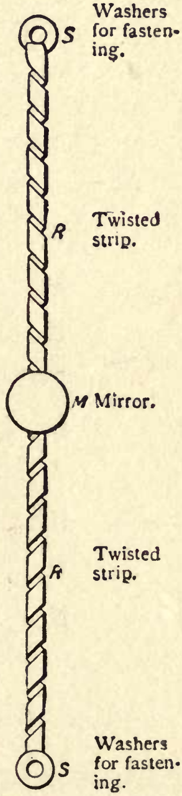


FIG. 36.—Strips for Sphingometer.

The Sphingometer.—This instrument may be employed to measure strains in one, two or more planes. Calibration is made for each test, if it is desired to note the elastic constants; if it is only desired to note the load at certain marked

[1] There are two other springs and columns not shown.

points, calibration is unnecessary. The adaptation of the instrument for measurement of strains in one or two planes will be fairly obvious if the type used for measurement in three planes is described.

The results obtained by experiment show that, with ordinary

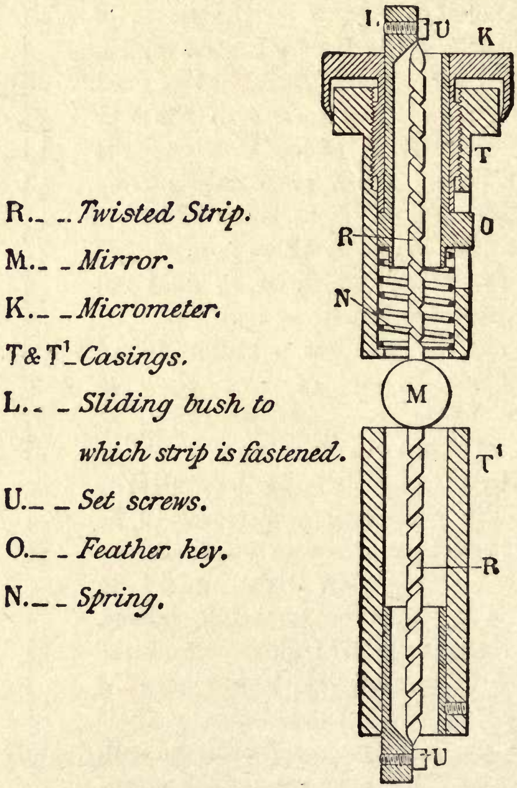


FIG. 37.—Section through Sphingometer Strip Holder.

methods of testing, there is a considerable variation in the stress on the bar. It is suggested that this is due to the fact that the load never passes directly through the axis of the specimen. It is therefore misleading to divide the total load registered on the testing machine by the area of the specimen in order to estimate the maximum stress on the material.

To avoid this error the author has devised a special form of extensometer for the purpose of measuring the strain on a specimen, in tension or compression, in three planes.

The general principle on which the instrument depends is that of the twisted strip used by Professors Ayrton and Perry, who have shown that the angular rotation of a mirror fastened

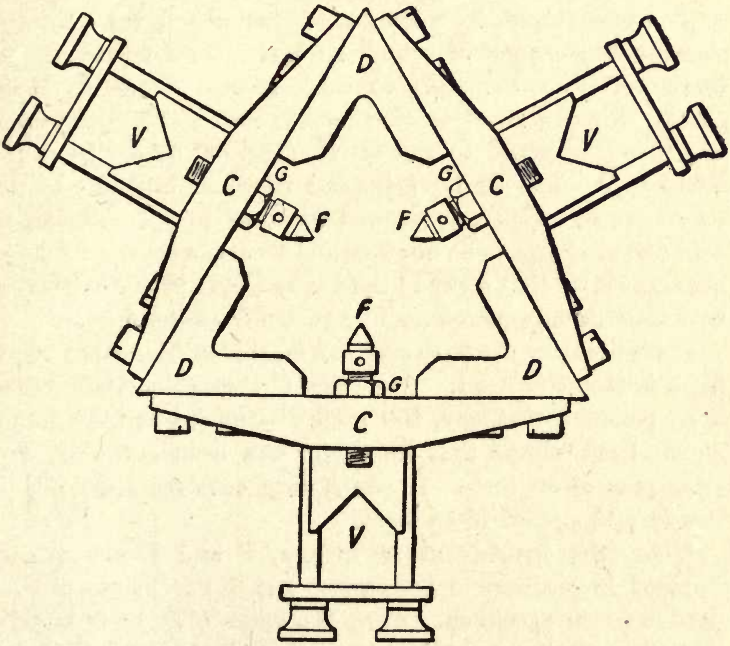


FIG. 38.—Strip Carrier and Specimen Grip for Sphingometer.

to a strip, as described below, is proportional to the extension (or shortening) of the length of the strip.

A piece of phosphor bronze, about 7 inches long, $\frac{1}{8}$ inch wide, and 0·004 inch thick, is used (Fig. 36). The material is divided into two lengths. At the centre an attachment is made so that a mirror (preferably of about 1 metre focus) may be fastened. One-half of the strip is then wound as a right-handed spiral, and the other half is wound as a left-handed spiral. At the two ends the strip is soldered to a thin

strip of metal, which has drilled through it a hole for a set screw. By means of this set screw at each end the strip is attached to a tube in which it is carried. By fastening this tube to a frame with two set screws, to secure the frame to the specimen, an extension of the length of the specimen between the two fastening screws can be measured.

During the author's experiments it was found that different strains were recorded on the same specimen if the points of attachment were moved round the bar. The instrument has, therefore, been arranged to take measurements in three planes, three tubes of the form shown in Fig. 37 being used, which were clamped to the carrier (Fig. 38) by means of the V-blocks V. The carrier grips the specimen centrally by the set screws F, which are screwed in so as to space the strips equi-distantly from one another and from the centre. A lamp is arranged so that a ray of light is reflected by the mirror on to a scale usually placed about 1 metre from the mirror.

For calibrating the strip a known extension is given by rotating a micrometer head. The effect of this is that the beam of light passes across, say, 100 scale divisions, when the micrometer head shows that the strip has been extended, say, $\frac{1}{1000}$ part of an inch. In which case each scale division is clearly $\frac{1}{100000}$ part of an inch.

When the instrument is in use, T and T′ are rigidly clamped in position to the upper and lower points of connection to the specimen. From the figure (37) it will be seen that when the micrometer head K is turned round, the bush L is forced down, compressing the spring N and shortening the strip R, R. This causes the mirror to rotate. If it is desired to change the direction of the beam of light across the scale during calibration, the micrometer head is turned round in either direction, the spring N forcing the bush L up when K is unscrewed.

It will be seen that the carriers are built up of three castings, C, which are interchangeable. They are screwed on to distance pieces, D. By altering the position of the points, at which the castings are fastened to D, the ize of

the triangle can be altered at will. This, therefore, gives the desired flexibility as regards the diameter of the specimen. Flexibility concerning the length between the gauge-points of the specimen is secured by altering the position of the sphingometer casing in the V-blocks. The limiting distance is the thickness of one of the castings C, which is about half an inch. In order to extend the length between the gauge-points beyond that shown in Fig. 37, a longer

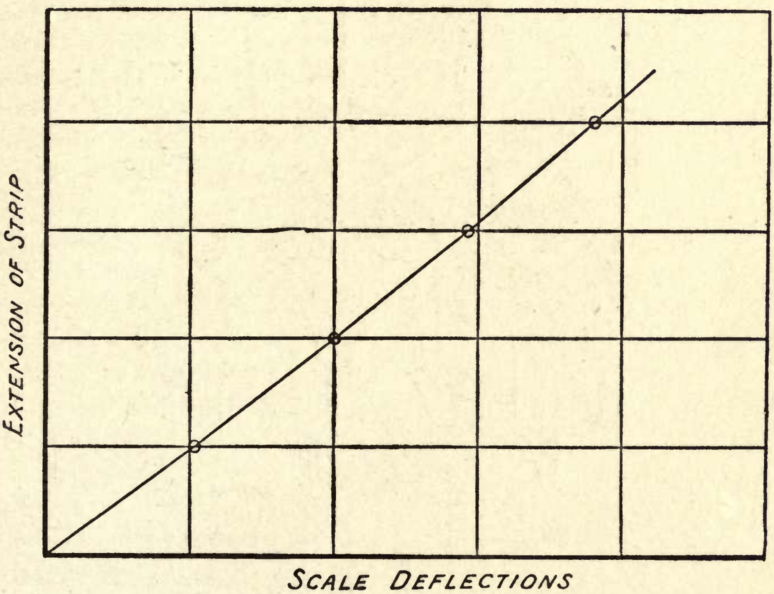


FIG. 39.—Calibration Curve for Sphingometer Strip.

tube is used at T′, and this can be extended indefinitely. It is, therefore, obvious that the distance between the gauge-points may be any length required from half an inch upwards.

Experience has proved that in calibration the most satisfactory method is to work across the scale in sections. This removes any error due to the non-curvature of the scale. It makes it also quite a simple matter to read direct the actual extension; Fig. 39 shows the method employed. It

will be seen that the readings are plotted against each other on squared paper.

The sphingometer is generally used for tension or compression tests, but by the addition of another strip and casing,

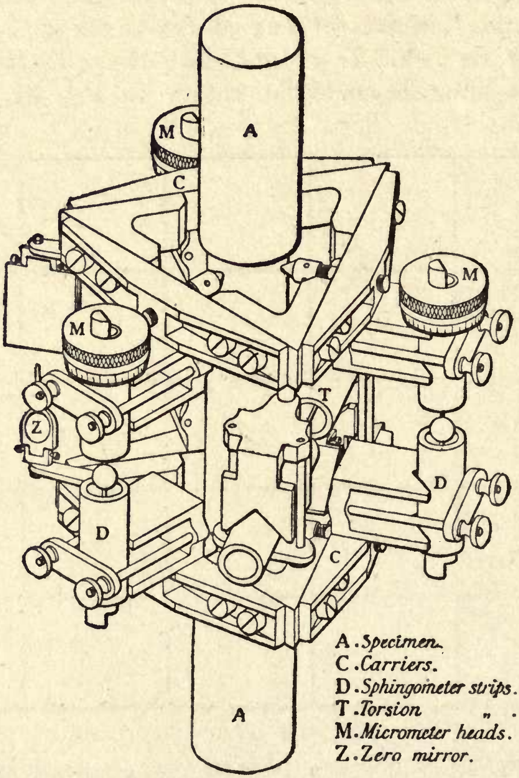


FIG. 40.—The Sphingometer fitted with Torsion and Tension Strips (for description of Torsion Attachment, see page 124).

torsion tests can also be carried out by the instrument. This torsion sphingometer is on a plane perpendicular to the plane of the tension strips. The illumination for this torsion mirror is obtained from the same lamp as that used for the tension mirrors. In Fig. 40 is shown an isometric projection of the instrument. The torsion fitting is explained fully later.

It has been found advantageous to use gauges in order

to insure that the two carriers are parallel. When the instrument is, for the first time, put on a specimen, the procedure is as follows: Steel distance pieces are placed in the V-blocks, made to hold the tubes in which are carried the strips. A gauge is then inserted at each corner of the carriers. This gauge can, of course, be altered for varying lengths of specimens. When the instrument is changed over from one specimen to another of a smaller or greater diameter it is convenient to use a gauge to ensure that all of the three fastening screws are at equal distance from the carrier frame. If it is desired to remove the instrument from one specimen to another one of the same gauge length, all that is necessary is to remove the sphingometer tubes and insert the steel distance pieces. The relative positions of the carriers cannot then change, and the framework is quite rigid.

One of the most important facts noticed by the use of the instrument is the variation in strain which accompanies a tensile or compressive stress. Bending, probably due to eccentric loading, occurs always. It is to be expected that when a specimen is in compression there will be bending. In order, therefore, to emphasise the importance of this fact of variation of strain the author will confine his remarks to the tension tests.

The problem of axial loading for a tension specimen is more difficult than would at first sight appear. A spherical seat (Fig. 17) may be used to secure alignment, but whatever precautions be taken to make the spherical seatings an accurate fit, it is doubtful whether they do pull into line when once the load is applied. In any case, it has been found from the results of tests that more uniform stress distribution exists when spherical seats are used than when the specimen is held in the ordinary wedge grips.

The unequal distribution of stress upon the specimen is the most determining cause of the unequal strains recorded during the experiments. It is the strain readings just previous to elastic failure which are most important. From

these we are able to deduce the maximum stress upon the material, and compare it with the mean stress. To show this clearly the author may mention a test, carried out by him, in which a specimen of mild steel showed from such deductions that a maximum stress of more than 13 tons per square inch was really on the specimen, while the mean stress recorded was 4·5 tons. This was an extreme case, but it would have been passed as normal under the usual conditions of recording extensions. In other words, it would have been recorded that the material had a load of 4·5 tons at elastic failure, from which the average stress is 37,980 lbs., whereas really the maximum stress was practically three times this amount. The results of a test are given on p. 113.

Autographic Recorders.—When a material is tested in tension or compression, certain strain-measuring instruments, to be described later, are of value for recording the stretch of the specimen under load, so long as it is elastic. There is, however, a critical load at which the strain ceases to be even approximately proportional to the stress, and after this load is passed the instruments useful for noting stretch during the elastic period are too sensitive.

There are two methods of procedure which may then be followed if the stretch, after the material is no longer elastic, is to be noted. An observer may take certain measurements of the distance between the gauge points, the load at the instant the reading is taken being carefully noted. Or an arrangement may be fitted so that both the load and the stretch are automatically recorded.

It is usually the practice to fit the recorder to the specimen before the test commences. The scale of the diagram on which the strain is thus automatically traced is important. If, as is usual, it does not exceed ten times that of the actual strain, the value of the diagram is in the fact that it gives a continuous record of the relationship of stress and strain after the material is no longer elastic. It is not sufficiently accurate for obtaining the value of coefficients within the period of elasticity. The following description of some

ingenious autographic recorders will show how these diagrams are obtained.

Unwin's Stress-Strain Recorder.—This apparatus, as its name indicates, automatically draws a stress-strain, or rather a load-extension diagram, without any readings being taken

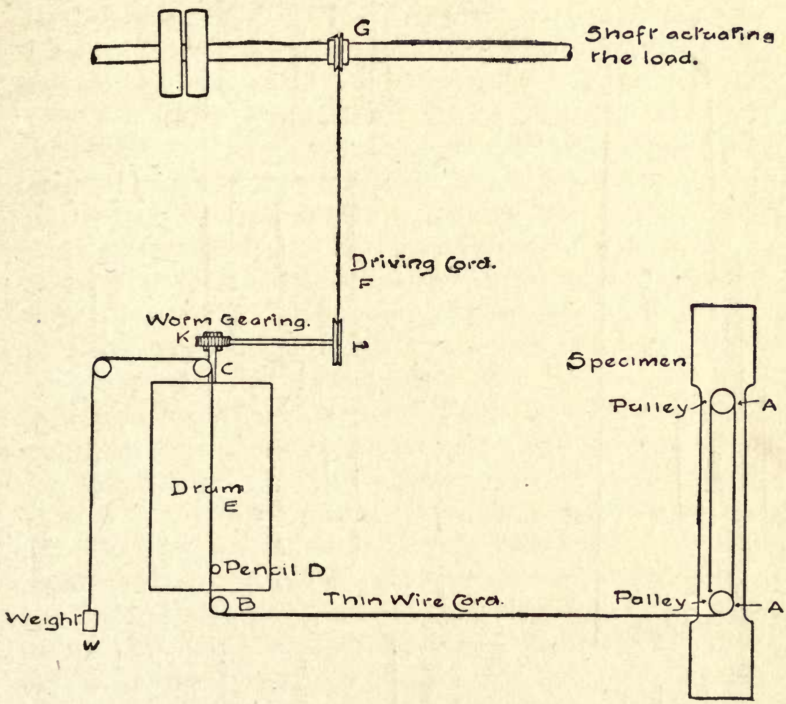


FIG. 41.—Unwin's Stress-Strain Recorder.

at all. This is done by using a rotating drum, as in the case of the steam-engine indicator. It is necessary to give the pencil two motions at right angles: one motion proportional to the load put on the specimen, and the other proportional to the extension produced by that load. To obtain the latter of these two motions, two clamps are fixed to the specimen, a gauge length apart, to each of which is fixed a pulley A A. Similar pulleys are fixed at B and C. A thin wire-cord, to

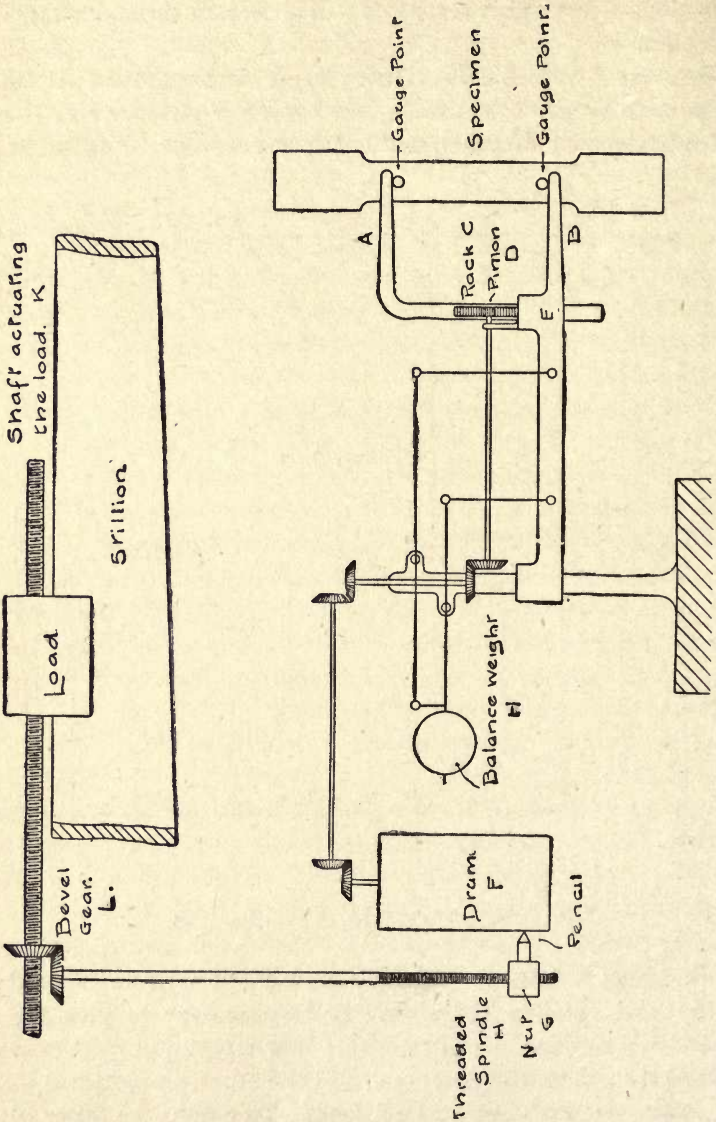


FIG. 42.—Wickstead's Stress-Strain Recorder.

which the pencil D is attached, passes round these pulleys, in the manner shown in Fig. 41, and teminates in a weight W

to keep all taut. Thus, by this arrangement, any extension of the specimen is reproduced to double the scale by the vertical movement of the pencil. Any total movement of the specimen, due to slipping in the grips, does not affect the pencil, as the wire between the specimen and the drum is made long enough to prevent this.

The motion proportional to the load, at right angles to the extension movement, is obtained by rotating the drum E, which gives essentially the same result as moving the pencil horizontally in the opposite direction. This is obtained from the shaft which moves the weight along the beam, and so actuates the load. As this shaft rotates, it turns the pulley G which drives the pulley H by means of a wire driving-cord F. The worm-wheel K is rotated by means of a shaft and worm from H, and so the rotation of the drum E is proportional to the movement of H, and hence to the load on the specimen.

Wicksteed's Apparatus.—The apparatus shown in Fig. 42 is also used for this purpose. Two arms A and B rest against projections fastened to the gauge-points. The arm B is supported in a horizontal position by means of levers and a balance weight H. The continuation of the arm A is bent downwards, and is guided in a vertical direction by a bearing E. This part of the arm is also provided with a rack C, which gears with the pinion D. Consequently, when the specimen stretches, the arm A moves relatively to B, and so rotates the pinion D. This rotation is transmitted through bevel gearing to the drum F, whose motion is thus proportional to the extension of the test bar.

The screwed shaft K, which moves the load along the stillion, rotates at the same time the bevel gear L. The motion is thereby transmitted to the threaded spindle H, which causes the nut G which carries the pencil to move upwards. The vertical motion then in this case is proportional to the load, and the horizontal one to the extension.

As it is only the *relative* motion of A and B that causes the pinion D to rotate, any total displacement of the specimen will not affect the movement of the drum.

Henning's Stress-Strain Recorder (Fig. 43).—As the extension of the test bar previous to the elastic limit is very small, and after that in the case of ductile materials comparatively

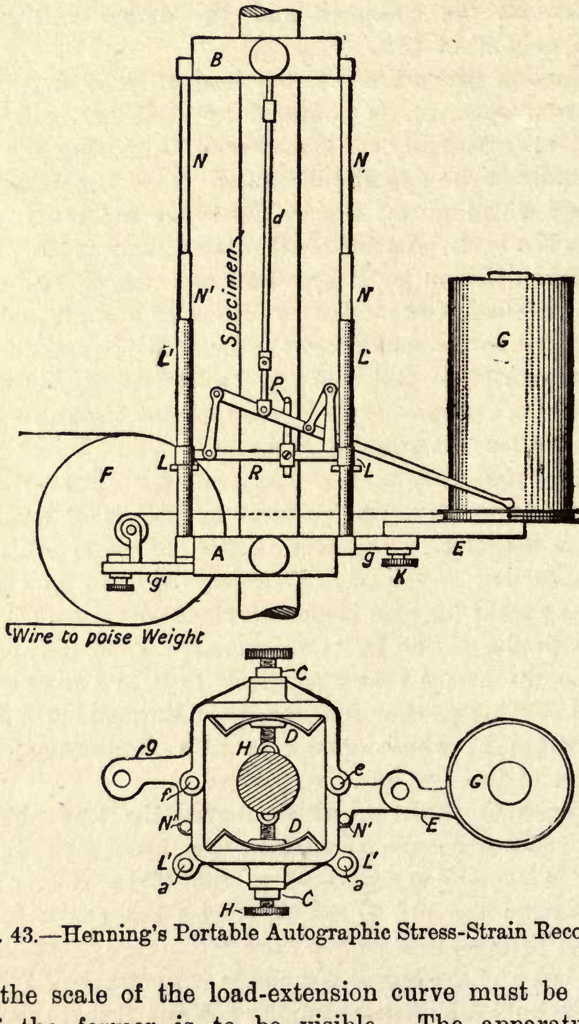


FIG. 43.—Henning's Portable Autographic Stress-Strain Recorder.

large, the scale of the load-extension curve must be a large one if the former is to be visible. The apparatus here described makes it possible to reproduce the first part of the diagram to a large scale, the extensions after the elastic limit

being automatically reproduced to a smaller one. It consists of two hinged frames A and B, one of which is provided with vertical rods N, and the other with tubes N N′ into which these fit, so that one frame steadies the other. The length of these rods is such as to keep the frames, at the beginning of the test, a fixed distance apart, though at the same time they are free to move axially when the specimen extends. The frames themselves are provided with spring-cushioned bushes C, and are hinged by taper plugs *e* and *f*. The bushes C are allowed to move backwards and forwards by means of the springs D. Through these bushes pass the screws H, which have hardened ends shaped like knife-edges, and are used to fasten the frames to the test bar. The lower frame A carries the drum G, on which the paper is fixed for recording the test. The frame A also carries a parallel motion, similar to that on steam-engine indicators. This mechanism rests on the bar R, carrying two tubes L, which slide on two rods L′ screwed into the frame A at *a*. It is operated by means of a connecting rod *d* by means of which the relative motion between A and B is thus transmitted to the pencil on an enlarged scale. The wheel F is also supported on A by the arm g^1, to which it is connected by a link and screw, so that it can swing to and from the marking point at will.

The drum G is rotated by a string which is wrapped round it, one end being connected to the travelling load, and the other to a weight which keeps it tight. In using this apparatus during a test, it is necessary to keep the lever absolutely balanced, as if this is not done the increments of load on the diagram will not coincide with the actual loads on the specimen. After the yield point is reached, the extensions become greater, so that it is necessary to reproduce them to a smaller scale. The hooked rod P is then so adjusted that at this point it automatically arrests the parallel motion, causing it to slide on the rods L′, so that all subsequent extensions are measured full size. The extensions previous to this are recorded to a scale of five times full size. When the test piece breaks, the instrument divides into two parts, the rods N and

tubes L simply sliding out of the tubes N′ and rods L′, while the parallel motion is suspended from frame B by means of the connecting rod. Should it be desired to use longer specimens it is only necessary to use a longer connecting rod. For compression tests a shorter connecting rod is used, so that the marking point will stand at the top of the drum at the beginning of the test, as its subsequent movement will then be downwards in direction.

Kennedy's Autographic Method.—In most autographic stress-strain recorders the stress recording movements depends on the movement of the poise weight. Now it is obvious that unless the poise is absolutely maintained the

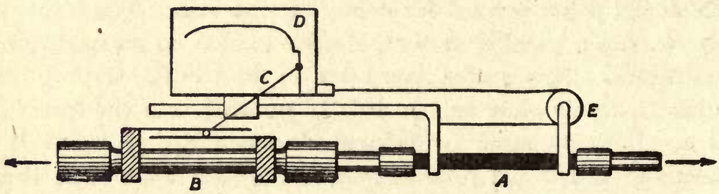


FIG. 44.—Kennedy's Automatic Stress-Strain Recorder.

diagram produced will not be strictly correct, hence attempts have been made to render the autographic apparatus entirely independent of the operator. Probably the instrument which best fulfills this condition is that devised by Prof. Kennedy. Fig. 44 illustrates in outline the method employed. A is the specimen to be tested, and this is connected by suitable grips to a second and larger bar of mild steel B. The latter is so chosen that at the load at which A will break B is well within that stress below which Hooke's law is exactly fulfilled. Attached to B is a "rolling pin" extensometer (see page 58), and the pointer C is arranged to trace out a line on a smoked glass screen D. Now it is obvious that if B is well within the elastic limit, the movement of the pointer C will be exactly proportional to the extension of B, which is in turn proportional to the load on both B and A. The screen D is attached to a fine wire passing over a pulley E and back to the other

end of the specimen under test. As A extends it is obvious that the movement of the screen longitudinally will be proportional to this extension, and hence the curve traced out by the pointer C will be a true stress-strain curve independent of any other adjustments to the testing machine. There is one rather unfortunate drawback to this apparatus, and that is

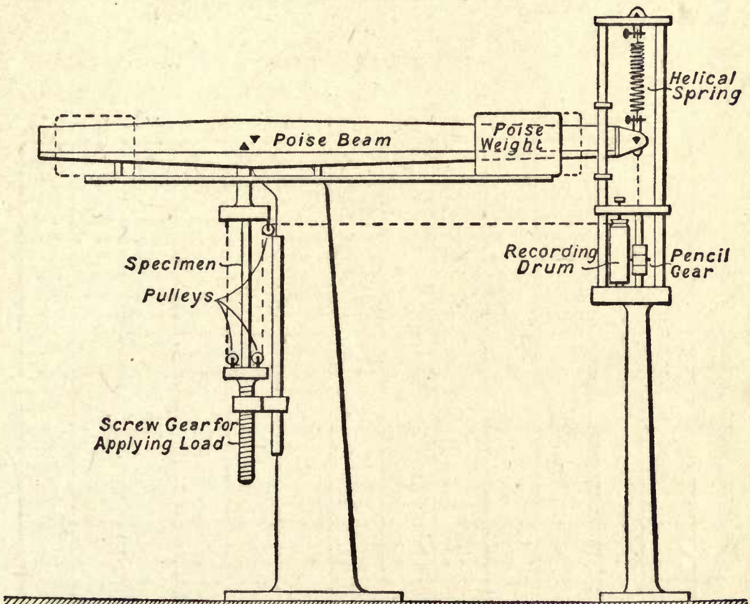


FIG. 45.—Autographic Stress-Strain Recorder as attached to a Single Lever Machine.

the fact that the movement of C will be in a circular arc. It would seem that, in spite of various attempts, this difficulty cannot be overcome without so increasing friction and inertia as to affect the accuracy more than is desirable.

The Wicksteed Recorder.—One of the most successful methods of obtaining an autographic diagram or stress-strain curve from single lever or even multiple lever machines is to place the poise weight at a position beyond the point of maximum load and then raise the end of the beam slightly

by means of a helical spring fixed to a support at the top It is then obvious that, if a specimen be fixed in the machine while the poise weight is just supported by the spring, the load on the specimen will be zero. If now we begin to load

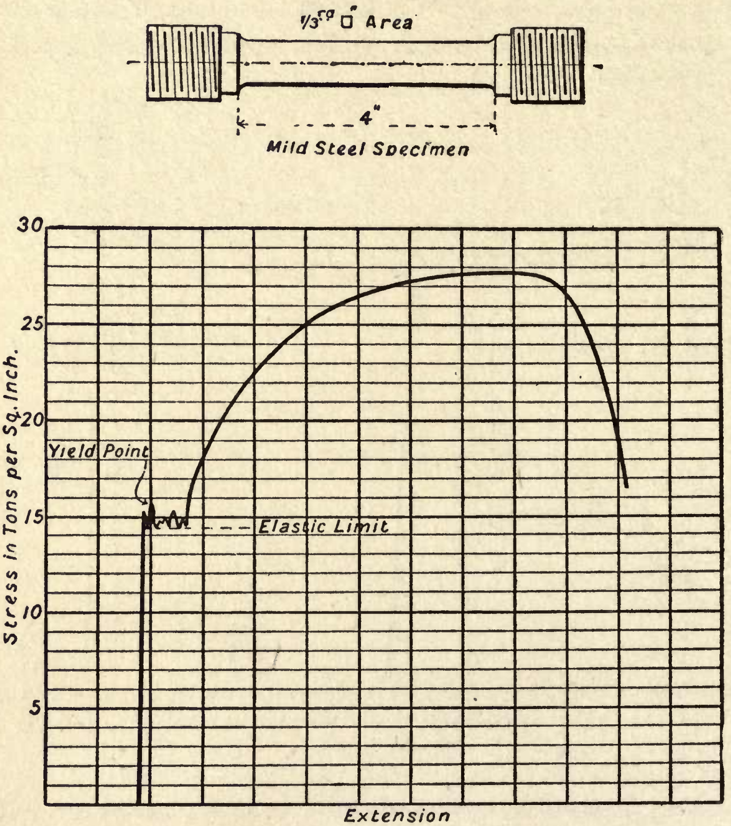


FIG. 46.—Autographic Diagram taken with Apparatus shown in Fig. 45.

the specimen by introducing water into the hydraulic cylinder or by any other means according to the particular design of machine employed it is obvious that we tend to raise the poise beam. Any upward movement of the poise lever, however, shortens the helical spring, and hence reduces the load carried by it. Hence, the unbalanced load must be taken

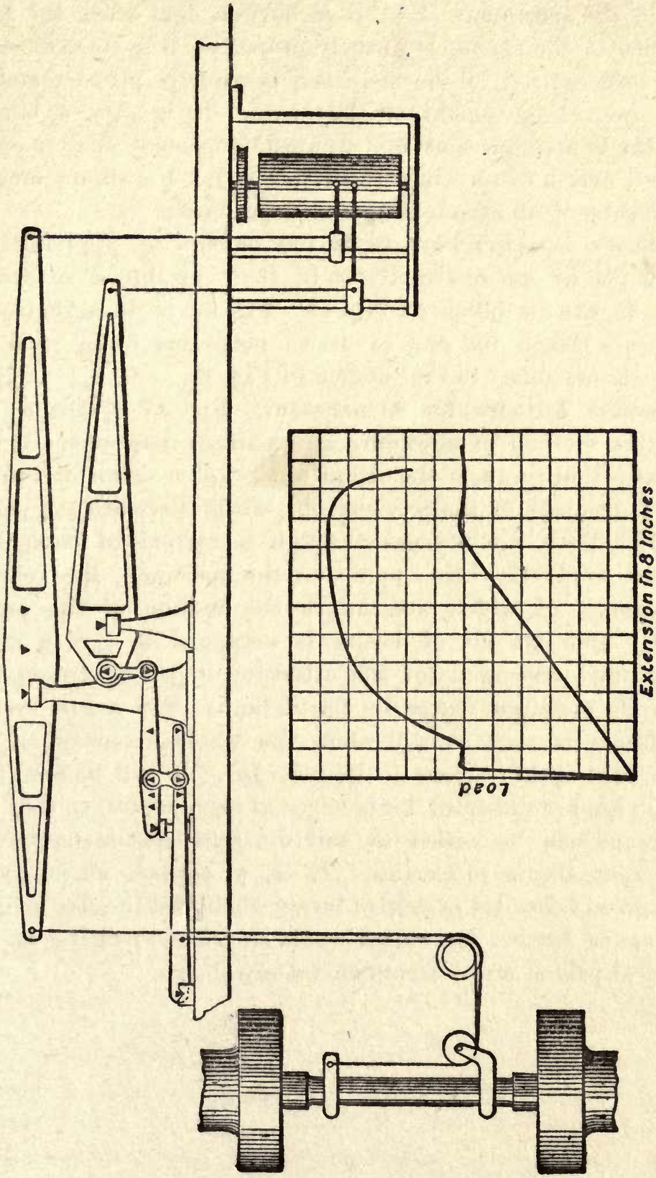


FIG. 47.—Autographic Stress-Strain Recorder with Double Pencil Gear giving Two Scales for the Extension.

up by the specimen. Now it is obvious that since the load carried by the spring is directly proportional to its extension, the load carried by the specimen is directly proportional to the upward movement of the beam. It is now a simple matter to arrange that this upward movement shall move a pencil over a drum while the latter is given a rotary motion by means of an attachment to the specimen.

Messrs. Buckton have taken out patents for applying this principle by various methods to their machines, of which Fig. 45 can be taken as typical. Fig. 46 is an autographic diagram taken on one of these machines fitted with an apparatus similar to that shown in Fig. 45.

Double Autographic Attachment.—Fig. 47 illustrates yet another method of obtaining stress-strain diagrams. It will be seen that there is the usual autographic drum driven by the movement of the poise weight, while there are two pencil gears. Both are worked through a system of compound levers from two fixed points on the specimen, the relative movement of which determines the motion of the pencil gear. One system of levers is arranged to give a much magnified movement for the extension of the specimen, and records extension below the elastic limit. The second system of levers is such as will allow the whole extension of the specimen up to fracture to be recorded. It will be seen that there are a number of knife-edges at each centre, so that the leverage can be varied to suit different specimens having different elastic properties. It is, of course, necessary to disconnect the first system of levers when past the elastic limit, otherwise further movement would smash the pencil gear. A typical pair of stress-strain curves are shown.

CHAPTER V

METHODS AND RESULTS OF TESTS ON MATERIALS

Tension Specimens.—There are many varieties of tension specimens, the size and shape varying according to the method of testing and type of machine to be employed. The kind of

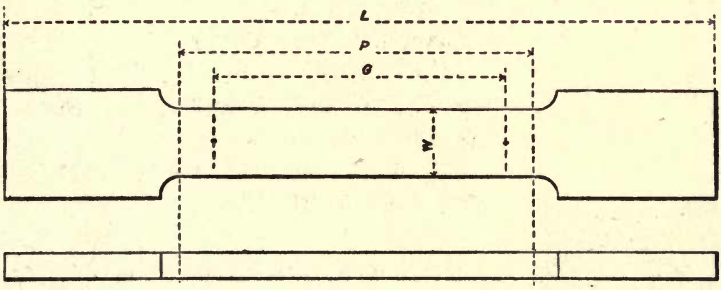


FIG. 48.—Standard Tension Specimen Plate.

specimen most usually met with for commercial tests is cut from the rolled metal, the shape being shown in Fig. 48.

The cross-section is generally about 2 inches by three-eighths, the ends, which are clamped in the grips being wider

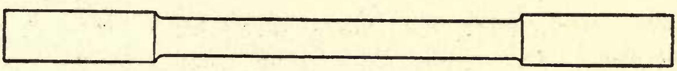


FIG. 49.—Typical Tension Specimen Bar.

so that the specimen is less liable to break outside the gauge length.

For bar tests, round specimens are employed, the ends being gripped in V-shaped grips. Such a specimen of normal proportion is illustrated in Fig. 49. Where greater accuracy is

required the ends of the specimen are threaded, this portion screwing into corresponding holders, which in turn are fastened to the shackles by ball and socket joints. This gives greater freedom in lining up, and enables the load to be applied more nearly axially to the specimen. Fig. 50 shows the type of end used with the grip shown in Fig. 17. The actual length on the specimen over which the test is made is called the "gauge length." This is most usually 8 or 10 inches on specimens of the size already illustrated, but of course tests are often carried out on specimens of much greater length than this.

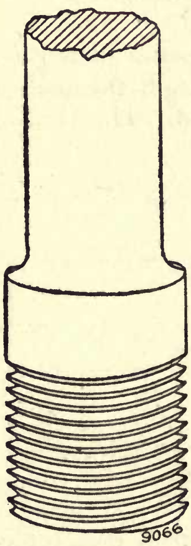


Fig. 50. — Screwed End for Tension or Compression Specimen.

Standard Test Pieces.—The following are the recommendations of the Engineering Standards Committee for *Sizes of Standard Test Pieces :*—

For Plates and other Structural Material (Test piece A, Fig. 48).

In all cases L to be approximately 18″.
,, ,, P ,, not less than 9″.
,, ,, G ,, 8″.

Width W for

Thickness over $\frac{7}{8}''$	maximum width	$=1\frac{1}{2}''$.
,, from $\frac{3}{8}''$—$\frac{7}{8}''$	,, ,,	$=2''$.
,, under $\frac{3}{8}''$	,, ,,	$=2\frac{1}{2}''$.

For Bars, Rods, and Stays.—(Test piece under 1 inch diameter) (Test piece B). Gauge length to be no less than eight times the diameter, and if provided with enlarged ends to be parallel for not less then nine times the reduced diameter.

(Test piece over 1 inch diameter) (Test piece F). Gauge length not less than four times the diameter, and if provided with enlarged ends to be parallel for a length not less than four and a half times the reduced diameter.

For Tyres, Axles, Forgings, Castings, Etc.—

<table>
<tr><td>(Test piece C.)</td><td>Diameter, ·564″ ($\frac{1}{4}$ sq. in.).
Parallel for not less than $2\frac{1}{4}$″.
Gauge length, 2″.</td><td rowspan="2">The form of ends to be made to suit particular method of gripping employed.</td></tr>
<tr><td>(Test piece D.)</td><td>Diameter, ·798″ ($\frac{1}{2}$ sq. in.).
Parallel for not less than $3\frac{3}{8}$″.
Gauge length, 3″.</td></tr>
</table>

Should a rather larger test piece than C or D be desirable, the following should be adapted:—

(Test piece E) Diameter ·977 in. ($\frac{3}{4}$ sq. in.). Parallel for not less than 4 inches. Gauge length $3\frac{1}{2}$ inches.

Test of a Ductile Material.—In a test of this kind there are certain recognised observations which should be taken. These are as follows:—

1. The load at which rupture occurs, thus giving the breaking stress.
2. The load at which yielding occurs, giving the yield point.
3. The elongation in the gauge length, giving the percentage elongation in the stipulated gauge length.
4. The reduction in the cross-sectional area, giving the percentage reduction in area.

Observations before the Experiment.—To enable these observations to be carried out the gauge length should be carefully marked off. Measurements should also be taken of the diameter of the specimen if round, or the breadth and thickness if flat. To obtain an accurate value, those measurements should be taken in three or more places, and the mean of these readings taken.

The specimen should also be marked with some distinctive letter, number, or sign, so that it may be easily recognisable for future reference. This mark should be made outside the gauge length, preferably on one end of the specimen.

The Test.—The specimen is then placed in the machine, and the load gradually applied. When a certain load is reached, it is observed that the specimen suddenly begins to elongate very appreciably with the further addition of little or

no load. The point at which this phenomenon occurs is known as the yield point, and it is said that the "elastic limit" has been reached. There is no difficulty in recognising this stage when reached, as the beam suddenly drops rapidly, and in consequence the pump has to be worked correspondingly fast to keep the beam floating.

When the yielding stage is passed, the specimen continues to stretch appreciably as the load is increased. As the breaking point is approached the specimen begins to draw out at its weakest section, where rupture will finally occur. In consequence of this decreasing cross-sectional area, the load

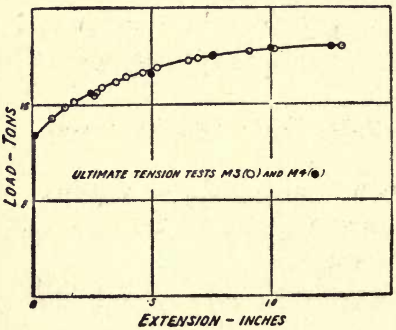


FIG. 51.—Ultimate Tension Test on Muntz Metal.

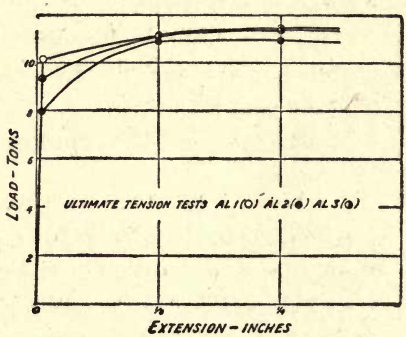
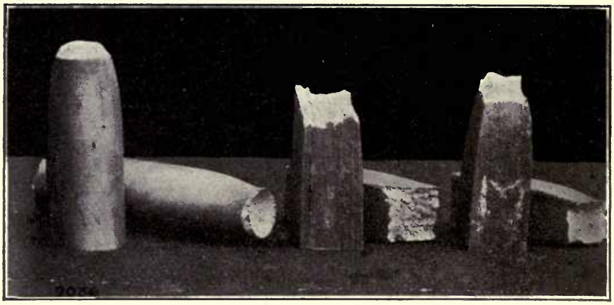


FIG. 52.—Tension Tests on Aluminium.

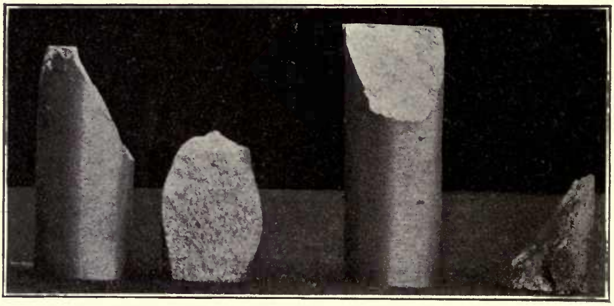
has to be run back, the maximum load which the specimen maintained being noted. When the specimen is exhibiting these qualities, it is said to be in the "plastic stage."

Rupture may occur without again increasing the load, though in some cases the load has to be run forward again before the specimen finally breaks.

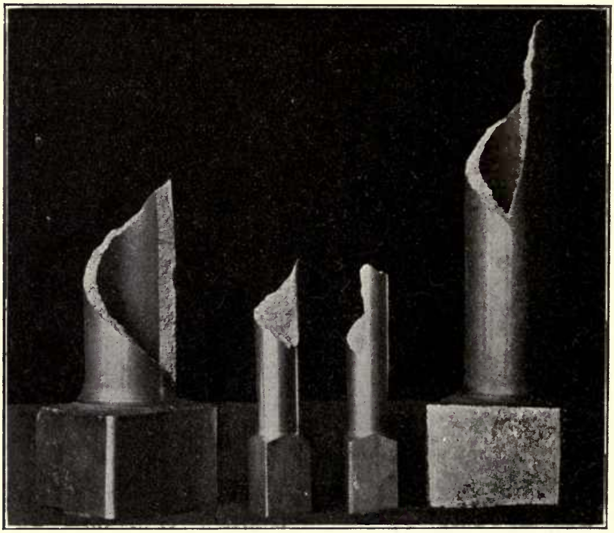
The characteristic properties of a material after elastic breakdown, and before fracture, are exhibited by the stress-strain curve, many examples of which will be found in this book. Such curves are, of course, either obtained autographically or from observations plotted from the readings of the load (read on machine), and the extension (read on the extensometer) in the manner previously described. Figs. 51



Fractures of Wrought-Iron and Mild Steel in Tension.



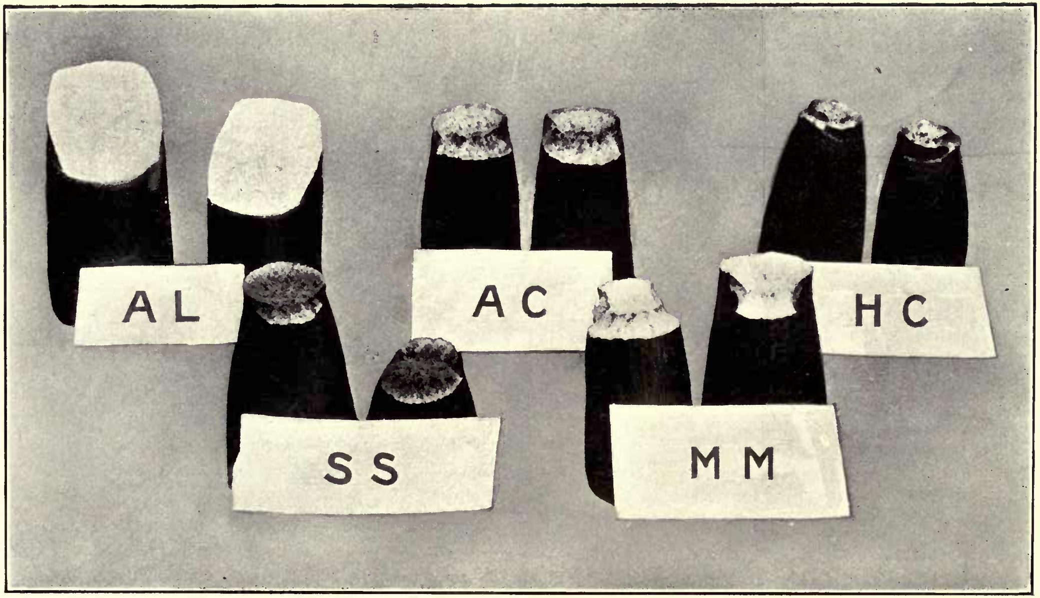
Fractures of Cast-Iron in Compression.



Fractures of Cast-Iron Specimens in Pure Torsion.

PLATE II.

PLATE III.



Fracture of Various Materials in Tension.

A L = Aluminium. A C = Arsenic Copper. H C = High Conductivity Copper.
S S = Mild Steel. M M = Muntz Metal.

and 52 show typical examples obtained by the author during tests on non-ferrous metals.

Observations after the Test.—After the specimen is removed from the machine the dimensions at the point of rupture should be taken, so that the reduced sectional area may be calculated. The two halves of the specimen should also be fitted as accurately as possible together, and the new distance between the two gauge points measured.

Results.—If

Mean original cross-sectional area of specimen	$= A_1$.
Gauge length of specimen	$= L_1$.
Cross-sectional area at point of rupture	$= A_2$.
Extended gauge length	$= L_2$
Yielding load on specimen (*i.e.* the load at yielding point)	$= W_1$.
Ultimate load on specimen	$= W_2$.

Then the percentage elongation $= \frac{L_2 - L_1}{L_1} \times 100$.

The percentage reduction in area $= \frac{A_2 - A_1}{A_1} \times 100$.

Stress at yield point on original area $= \frac{W_1}{A_1}$.

Ultimate stress or breaking stress on contracted area $= \frac{W_2}{A_2}$.

Usually the units employed are the inch and the pound, and the stresses are therefore calculated in pounds per square inch.

Characteristics of Rupture.—Mild steel and good wrought-iron show much contraction at the point of rupture. Stronger steels are less ductile. Brass is a very ductile material, and exhibits a silky section when broken (see Plates II. and III.).

Distribution of Extension.—Let the gauge length of the specimen be divided into equal divisions before testing. After rupture has taken place the extension in each division is measured, and plotted as ordinates on a base line representing the equal divisions on the specimen. Fig. 53 shows the curve obtained from a ductile material. The distribution of extension

TABLE I.

TENSION TESTS—DUCTILE MATERIALS.

Gauge length.	Dimensions.			Yield Point.		Maximum Load.		Extension.		Reduced Area.			Reduction of Area.		Mark.	Material.
	Breadth	Thickness.	Area.	Load.	Per sq. inch.	Load.	Per sq. inch.	Total.	Per cent.	Breadth	Thickness.	Area.	Total.	Per cent.		
				Tons.	Tons.	Tons.	Tons.									
4″	·747	Dia.	·438	7·31	16·69	10·69	24·41	1·156	28·91	·585	Dia.	·269	·169	38·58	3.S.	Best Staffordshire.
8″	·758	Dia.	·451	6·80	15·08	10·39	23·04	2·28	28·52	·519	Dia.	·212	·239	52·99	4.Y.	Best Yorkshire.
8″	1·012	·577	·585	9·04	15·48	15·87	27·17	2·28	28·52	·712	·367	·262	·323	55·25	1.S.B.P.	Steel Boiler Plate.
8″	1·000	·484	·484	14·48	29·92	23·28	48·10	1·31	16·41	·790	·365	·288	·196	40·5	1.S.S.	Spring Steel.
8″	1·010	·522	·527	3·18	6·03	7·55	14·33	3·28	41·02	·702	·343	·241	·286	54·27	1.C.P.	Copper Plate.

The table gives the results obtained on five different materials, and may be taken as typical of the method of recording commercial tension tests. It will be seen that the loads usually recorded are those noted at the yield point and the maximum load. The other measurements made will be seen from the table.

is not at all uniform, but increases very greatly towards that section where fracture occurs.

This indicates the importance of specifying over what gauge length the percentage elongation is taken, since the smaller the gauge-length the greater is the percentage elongation.

Tests of Non-Ductile Materials.—Cast-iron furnishes one of the best examples of non-ductile materials. Such materials have no elastic limit, nor appreciable yield point. When testing, it is of great importance that no bending be set up

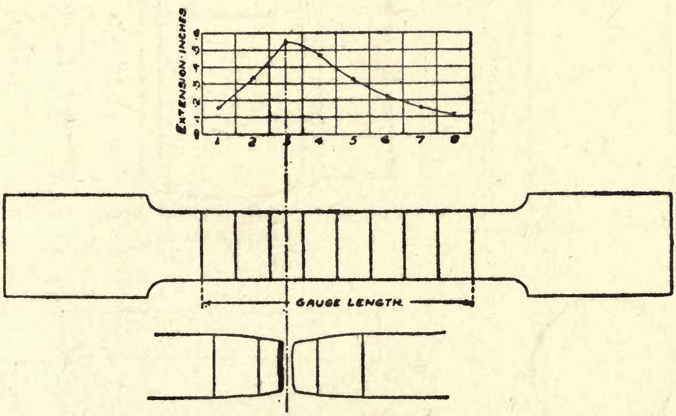


FIG. 53.—Distribution of Extension.

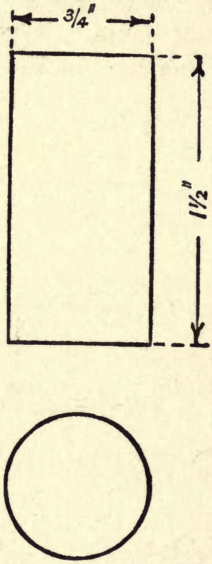
due to imperfect clamping in the shackles, as this would materially distort the result. The best way to ensure perfect alignment is to employ the ball and socket tension joint already described.

TYPICAL RESULT—CAST-IRON.

Mark.	Diameter.	Area.	Maximum Load.	Maximum Stress.
1 C.1.	·750	·442	5·94 tons.	13·43 tons per sq. in

Compression Tests.—The specimens for compression tests are generally short cylinders, a very usual size being $1\frac{1}{2}$ inches long by $\frac{3}{4}$ inch in diameter, as shown in Fig. 54. Whatever may be the size of specimen chosen, however, it should be taken as a general rule that when only the *ultimate* strength is to be determined the length should not

exceed two to three times the diameter. If this ratio of length to diameter be exceeded, bending of the specimen may occur, so that its failure may be due, not to compression alone, but to a combination of compression and bending. For purposes, other than ultimate resistance tests, specimens of 1 inch diameter and 10 or 20 inches in length



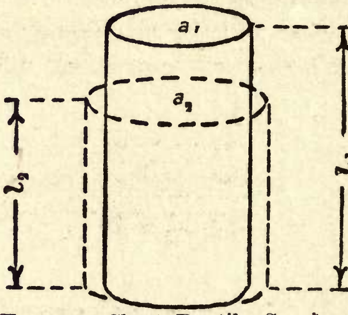


FIG. 55.—Short Ductile Specimen in Compression.

FIG. 54. — Typical Compression Specimen.

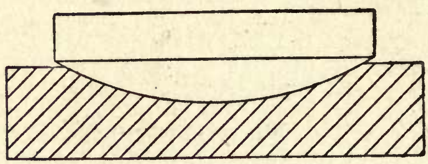


FIG. 56.—Ball and Socket Joint.

may be used. Great care must be taken to ensure axial loading.

The Test.—The machine is fitted up for compression tests, and the specimen, after its length and diameter have been carefully measured, is inserted between hardened steel plates. It is preferable to have one of these plates fitted with a ball joint (Fig. 56) as then the pressure is distributed evenly over the two faces of the specimen.

The load is applied, and increased by equal increments, the length of the specimen together with its mean diameter being measured in each case.

This mean diameter is a somewhat indeterminate quantity. An easier method of obtaining this dimension is as follows :—

In Fig. 55 let a_1 and l_1 be the mean diameter and length respectively of the specimen before testing.

Let a_2 and l_2 be the new dimensions after a certain load is applied. Then since the volume of the specimen remains approximately constant,

$$a_1 l_1 = a_2 l_2.$$

$$\text{Hence } a_2 = a_1 \frac{l_1}{l_2}.$$

Consequently all that it is necessary to do after each new load is applied is to measure the new length, from which the new mean diameter can be obtained from the above simple equation. The length of the specimen can be measured by a scale and vernier without removing the specimen from the machine. Owing to the fact that the specimen continues to compress for some time after each load is applied, it is important that a stipulated and definite time should elapse between the application of each new load and the corresponding reading of the new length.

A typical table of readings is given below :—

SPECIMEN—MILD STEEL.

Dimensions—Diameter, $\frac{3}{4}''$; Length, $1\frac{1}{2}''$.

Load in lbs.	Total Compression.	New Length, l_1 in inches.	New Area, $a_2 = a_1 \frac{l_1}{l_2}$.	Real Stress $\frac{\text{Load}}{a_1}$ lbs. per sq. in.
0	·000	1·500	·442	0
6,000	·006	1·494	·444	13,520
12,000	·013	1·487	·446	26,900
15,000	·016	1·484	·447	33,550
18,000	·057	1·443	·459	39,220
24,000	·098	1·402	·472	50,750
30,000	·167	1·333	·497	60,350
36,000	·251	1·249	·531	67,800
42,000	·343	1·157	·573	73,400
51,000	·478	1·022	·648	78,750
57,000	·523	0·977	·678	84,200
66,000	·662	0·838	·791	83,500

Curves plotted from these figures are shown in Fig. 57. It will be observed that yielding takes place at a load of about 15,500 lbs., giving a stress on the specimen of 34,500 lbs. per sq. in.

Appearance of Specimen.—As the tests on the mild steel

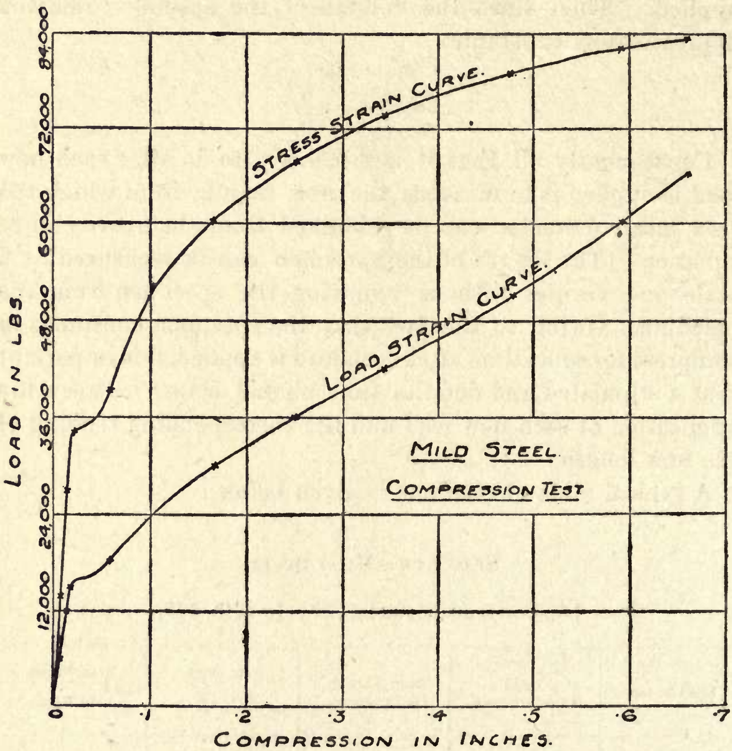


FIG. 57.—Real and Apparent Stress-Strain Curves in Compression (from single observations).

proceeds the specimen is seen to bulge, finally assuming a barrel-shaped form, and if the load is increased to a sufficiently large extent, cracks and seams, approximately parallel to the axis of the specimen, appear as seen in Fig. 58.

Wrought-iron would show very much the same characteristics, except that the cracks would probably be more pronounced.

Cast-Iron.—If cast-iron be tested in compression, failure will occur in a very different way from that of wrought-iron or mild steel, since the specimen fails by shearing. To thoroughly understand this, it is necessary to inquire into the manner in which the shear stress varies on planes inclined to the axis through which the pressure acts.

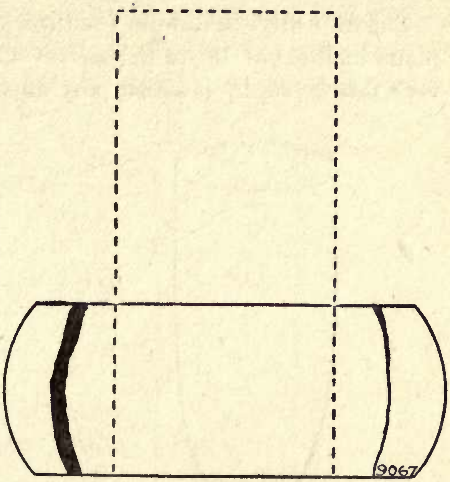


Fig. 58.—Appearance of Ductile Compression Specimen at Failure.

Let a = cross-sectional area of the specimen.

Let f = intensity of stress on planes normal to axis.

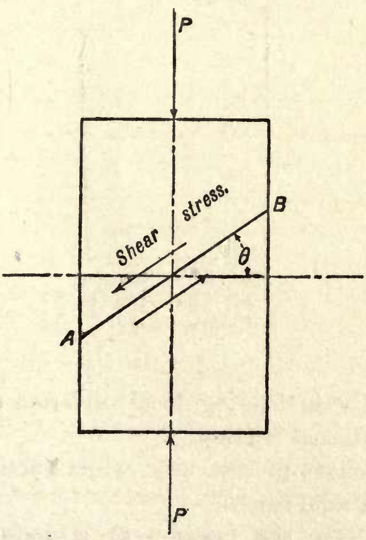


Fig. 59.—Shear Stress on Cast-Iron.

Resolve this stress into forces parallel and perpendicular to plane A, B (Fig. 59).

Then shear force on plane AB $= f.a. \cos \theta$.

But area of plane AB $= \dfrac{a}{\sin \theta}$.

$\therefore$ Shearing stress on plane AB $= \dfrac{f.a. \cos \theta}{\dfrac{a}{\sin \theta}} = f \cos \theta \sin \theta$.

From which it is seen that the shear stress is a maximum when $\theta = 45°$.

Theoretically, therefore, fracture should take place along a plane inclined at 45° to the axis. This is found to be so, or very nearly so, in practice, any deviation from theory being

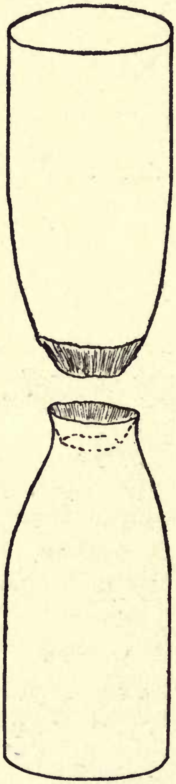


FIG. 60.—Fracture of Ductile Material in Tension.

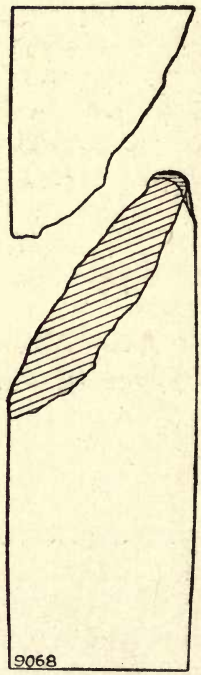


FIG. 61.—Fracture of Cast-Iron in Compression.

probably due to non-uniformity in loading, local variation in the material, or possibly to internal friction.

Brittle hard materials all behave in this way, while ductile plastic metals fail similarly to mild steel.

Cast-Iron in Compression.—If the fracture of a ductile specimen, which has been broken by application of a direct

pull, be examined, it will be found that failure has not been the result of tearing across a plane section perpendicular to the axis, but that shearing has taken place along the surface of a cone of semi-vertical angle, approximately $\frac{\pi}{4}$ (Fig. 60). If a specimen of the same material be taken and tested in compression it will be found that, if the specimen is too short for buckling to take place, there will be no definite fracture (Fig. 58). A possible explanation is that, when the specimen is short enough for buckling not to occur it is too short for shearing to take place in one fracture. There will therefore be an internal crumbling along numerous shearing planes, which in a plastic material may not exhibit itself as a separation of the specimen into so many pieces. In a brittle material (Fig. 61) the shearing fracture produced by direct compressive stress is very marked. So far, then, we may say that in at least ductile materials, directly stressed, shearing is the governing factor. Let us examine how such a stress arises and what its magnitude will be. Consider a specimen of unit-cross-section subjected to a steady pull of P lbs. (Fig. 62). Then on any section perpendicular to the axis there will exist a tensile stress numerically equal to P. On this plane there will be no tangential stress since P can have no component at right angles to itself. On a plane

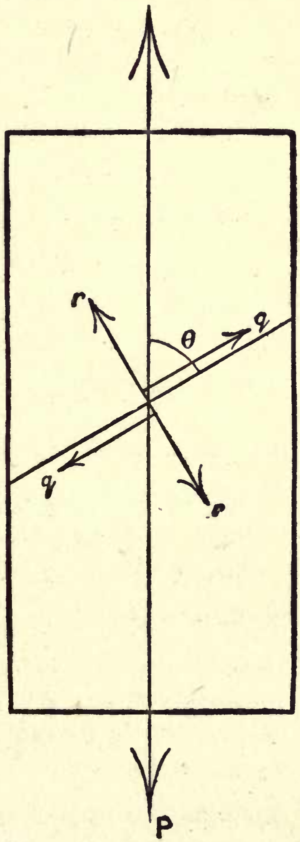


FIG. 62. — Resolution of Forces in a Specimen subjected to Tension.

section inclined to the axis there will, however, be in general two stresses, one normal and the other along the plane of the section. Consider the equilibrium of one of the portions cut off by the plane of section. We have along the axis a stress $= \mathrm{P}$, along the plane a shearing stress, say, q, and perpendicular to it a normal stress, say r. These three must equilibrate.

Resolving vertically we have

$$\frac{r}{\sin\theta}\sin\theta + \frac{q}{\sin\theta}\cos\theta = \mathrm{P} \text{ or } r + q\cot\theta = \mathrm{P} \quad \ldots \quad (1)$$

Resolving horizontally we have

$$\frac{r}{\sin\theta}\cos\theta = \frac{q}{\sin\theta}\sin\theta \text{ or } q = r\cot\theta \quad \ldots \quad (2)$$

whence $$r = \mathrm{P}\sin^2\theta \quad \ldots \quad \ldots \quad \ldots \quad (3)$$
and $$q = \mathrm{P}\sin\theta\cos\theta \quad \ldots \quad \ldots \quad (4)$$

This last equation may be written as $q = \frac{\mathrm{P}}{2}\sin 2\theta$. The maximum value of $\sin 2\theta$ is 1 and occurs when $\theta = \frac{\pi}{4}$. Hence we see that a direct stress induces shear on planes inclined to the axis and that this shear stress is a maximum on planes inclined at 45° to the axis, or their envelopes (cones of semi-vertical angle $\frac{\pi}{4}$). Its value is then half the maximum direct stress. Therefore if no disturbing factors enter into the question a directly stressed specimen should, if the shearing stress is the determining factor, shear along a surface inclined at 45° to the axis. The symmetrical surface fulfilling this condition is a cone of semi-vertical angle $= \frac{\pi}{4}$. This fracture allows separation in the case of a tension specimen, but not so in the case of compression. A specimen fractured by direct push therefore separates along a plane surface.

It has already been indicated that the measurement of this angle of yield for a ductile specimen, subjected to compression, presents very considerable difficulties. In the case of tension the difficulties, though less manifest, are none the less real. The conical fracture is very apparent, and the measurement

of the angle is easy; it must, however, be remembered that the angle which can be measured gives only an approximate indication of the form the conical surface assumed when the material yielded, and was virtually destroyed. When the yield point is passed the material offers no permanent resistance to the application of the force; it is, in effect, a liquid, and the increase of the force merely shortens the time occupied in viscous flow, and until actual surface separation must take place. The plastic drawing out will deform the surface along which yield takes place and which probably also forms the surface of separation.

In a ductile material it is, therefore, as has been seen, a matter of no little difficulty to determine exactly the surface along which yielding occurs. In a brittle material under compression the problem is considerably simpler, and its consideration may throw some light on what really happens within a stressed material. In a specimen of cast iron the fracture is perfectly definite, and, as no plastic flow occurs, it may be assumed that the surface of yield coincides with the surface of separation. Therefore if the maximum value of the shear stress is the only determining factor, the fracture should take place along a plane inclined to the axis at exactly 45°. This is never found to occur; the angle θ is consistently less than 45°, and a reason has to be sought.

Let us examine the following results obtained on a specimen of cast iron.

Diameter = ·727 inch.
Length = 2·125 inches.
Breaking load = 19·25 tons.
$\theta = 33°$.

Maximum shear stress on plane—
where $\theta = 45° = 23·2$ tons per sq. inch.
Direct stress on this plane = 23·2 tons per sq. inch.
Shear stress on plane of fracture = 21·2 tons per sq. inch.
Direct stress on plane of fracture = 13·7 tons per sq. inch.

It will be seen that fracture took place along a surface where the shear stress was 2 tons per sq. inch below, or, roughly, 10 per cent. lower, than the maximum. It will, however, be noticed, that the normal stress on the breaking section was considerably lower than that on the section where the shear stress was a maximum. This immediately suggests the fact that a direct push between two surfaces increases the resistance to their shearing or sliding over one another. The effect, in fact, is very akin to friction, and a theory, usually known as Navier's theory, has been developed on these lines, and is as follows.

Let the true shear resistance, when no normal stress is exerted between the surfaces, be f. Then if r is the normal stress on the section, we may suppose that the actual shearing resistance offered (q) is of the form $q = f + \mu\, r$; but $q = \mathrm{P} \sin\theta \cos\theta$, and $r = \mathrm{P} \sin^2\theta$. $\therefore f = \mathrm{P}(\cos\theta \sin\theta - \mu \sin^2\theta)$.

Fracture will take place across the section where f is a maximum, *i.e.*, where $\frac{df}{d\theta} = 0$.

$$\frac{df}{d\theta} = \mathrm{P}\cos\theta\,(\cos\theta - \mu\sin\theta) + \mathrm{P}\sin\theta\,(-\sin\theta - \mu\cos\theta) = 0.$$

$$\therefore \cos^2\theta - \sin^2\theta = 2\,\mu \sin\theta\cos\theta. \quad i.e., \ \mu = \cot 2\theta.$$

If ϕ = angle of friction, then $\tan\phi = \cot 2\theta$.

$$\therefore 2\theta + \phi = \frac{\pi}{2}, \text{ and } \theta = \frac{\pi}{4} - \frac{\phi}{2}.$$

Taking the particular case where $\theta = 33°$, we have $\phi = 24°$ or $\mu = {\cdot}45$ approximate. Whether this theory is at all justifiable is for future research to determine.

The following values have been obtained from compression tests on cast-iron specimens. It will be a good exercise for the student to measure the angles of fracture and evaluate the co-efficient μ. It should be remembered that discrepancies may be due to (1) non-homogeneous material; (2) the fact that yield point and ultimate fracture loads are not necessarily co-incident. This may account for the varying results recorded in the following table.

TABLE II.

COMPRESSION TESTS ON CAST-IRON.

D in inches.	L in inches.	W in tons.	$P=\frac{W}{A}$ in tons per sq. inch.	θ in degrees.	μ	f in tons per sq. inch.
·916	1·662	37·09	56·3	29	·625	15·6
·752	1·470	22·15	49·9	34	·404	16·8
·966	1·675	41·65	56·8	33	·445	18·5
·904	1·807	26·89	41·9	30	·577	12·1
·815	1·760	28·61	55·0	31	·532	16·5
·943	1·652	27·33	39·1	28	·675	10·4
·816	1·762	26·92	51·5	28	·675	13·6
·961	1·663	33·46	46·1	28	·675	12·2

Autographic Diagrams.—An autographic diagram gives much fuller information as to the behaviour of a metal under test than does the mere breaking test.

Not only does it give all the results obtainable from a test to rupture, but in addition the extension of the bar at any load can be easily obtained from it, together with the work expended in breaking the bar.

Before taking the diagram the necessary measurements of gauge length and cross-sectional area of the specimen are made. The specimen is clamped in the grips and the autographic apparatus fitted. The load is then run on slowly, the beam being kept floating by means of the pump. Great care should be exercised to prevent the beam touching the stops, otherwise the diagram produced will not be a true one. This difficulty will be particularly pronounced at the yield point and near the point of rupture. At the yield point, owing to the comparatively rapid change in length of the specimen, the pump has to be worked continuously with little or no increase in load. Nearing the rupture point with ductile materials the load has actually to be run back owing to the rapidly diminishing cross-sectional area of the specimen.

It was stated previously that the load was run on and the beam kept in equilibrium by means of the pump. This, in a sense, is hardly true when the pump is worked from the shop

shafting. When such is the case it can only be operated at some definite speed, so that the beam is kept floating by the rate at which the load is applied.

Fig. 63 shows a typical diagram for mild steel plates.

If the cross-sectional dimensions of the specimen be

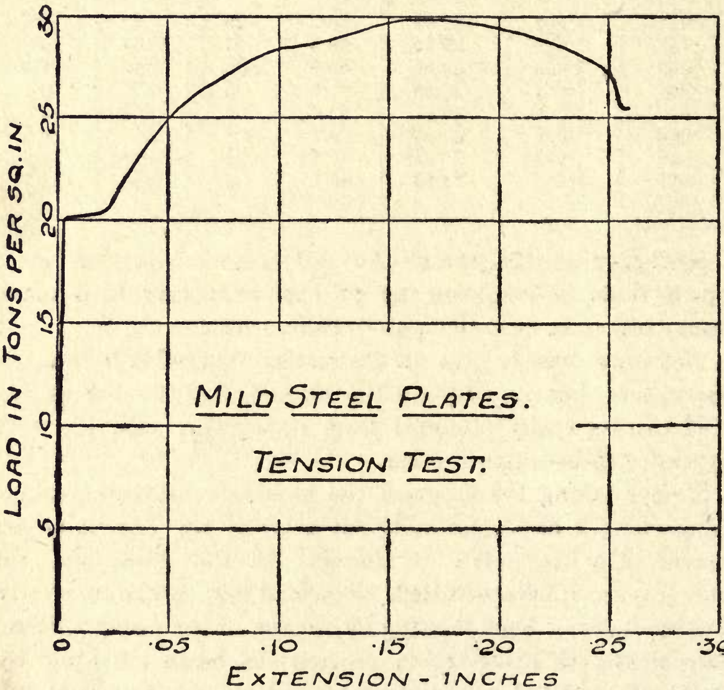


Fig. 63.—Mild Steel Plates in Tension (Autographic Diagram).

measured at definite loads during the tests, a means is given of determining the actual stresses on the reduced section of the bar.

A second curve plotted from results obtained thus is shown in Fig. 64.

Raising the Yield Point.—The autographic diagram affords a very convenient method of verifying the statements regarding the raising of the yield point by a process of repeated loading. The phenomenon is as follows: Let the load be

carried a little beyond the initial elastic limit, and allowed to remain so for a certain time. On removing the load, and then again running it on, the specimen will be found to yield not

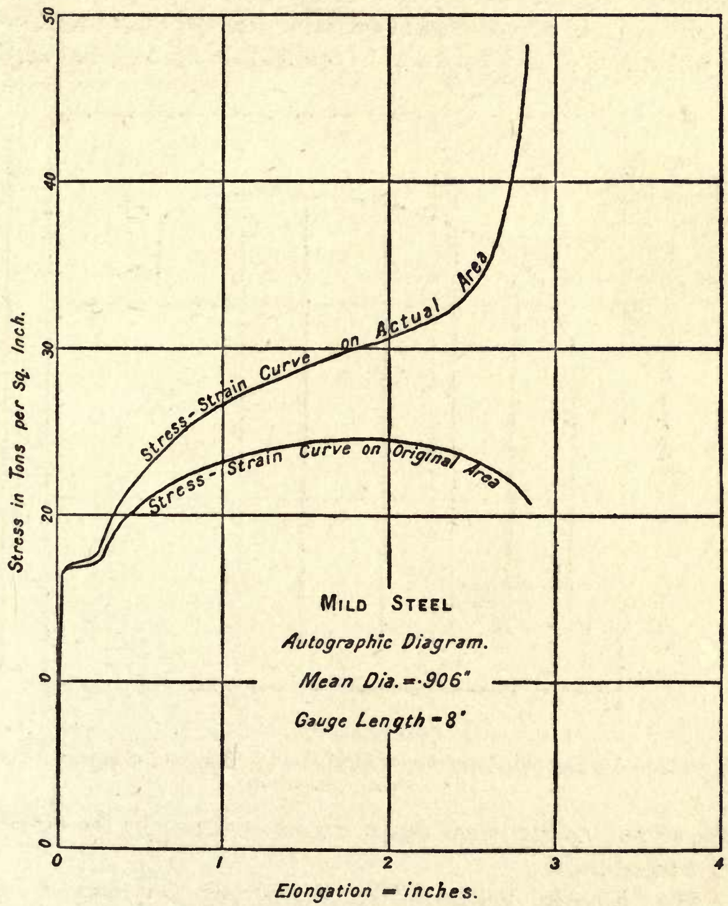


FIG. 64.—Curves of Real and Apparent Stress.

at the initial or primitive elastic limit, but at about the load originally applied to the specimen. By such a process the elastic limit may be raised until finally it coincides with the breaking load of the specimen. This is shown in Fig. 65.

This phenomenon of raising the yield point by repeat loadings is but one of a number which can be conveniently investigated by the student. For a full discussion of the change of elastic properties by mechanical and heat treatment the student should refer to proceedings of scientific and technical societies. It will suffice to give here a few typical examples together with

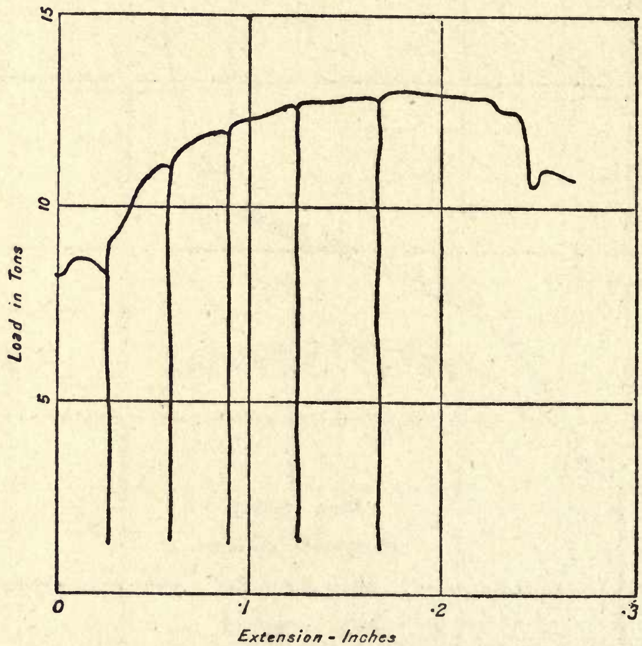


FIG. 65.—Autographic Diagram of Mild Steel in Tension, showing Effect of removing temporary.

the corresponding stress strain curves obtained by the author and his students.

The Elastic Range.—The theory was enunciated by Bauschinger that a change in the elastic limit follows the extension of a specimen, and that if mild steel has an elastic limit of, say, 13 tons in a tension test, and the same value in a compression test, then if the material be overstrained in tension until the new elastic limit is raised to, say 16 tons, the elastic limit in compression will be 10 tons. In other words,

the elastic range of the material is 26 tons. In July, 1908, the author made tests. Stress distribution was not taken into account, and the results are therefore not within an accuracy of 5 per cent. The first elastic limit was 13 tons. By increasing the tension elastic limit 2·7 tons, the compression elastic limit was lowered 2·5 tons. A full account of these

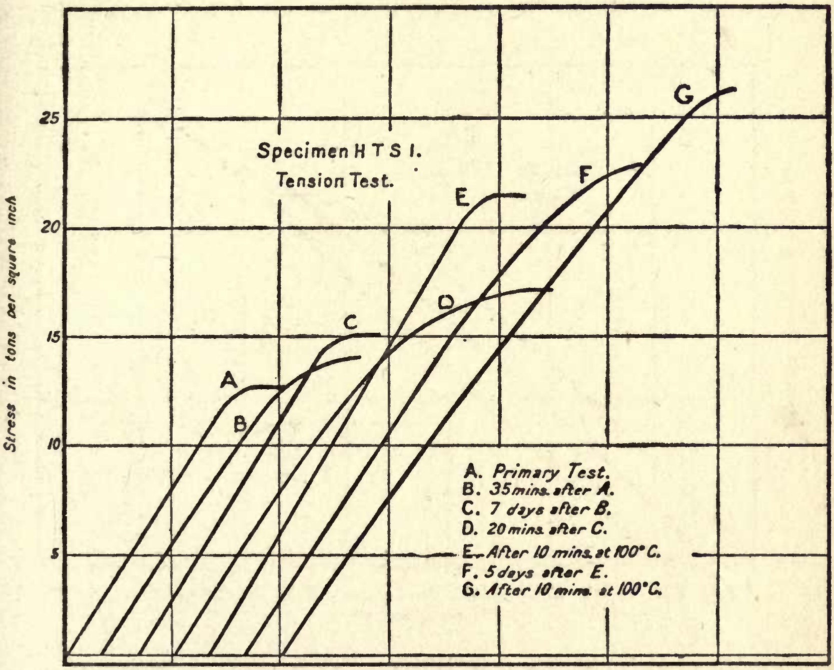


FIG. 66.—Effect of Time and Low Heat Treatment on Mild Steel in Tension.

tests—considered unsatisfactory for various reasons set forth—are to be found in the *Journal of the Institution of Junior Engineers*, July, 1909.

Mr. Leonard Bairstow, shortly afterwards, published in Vol. CCX., Series A, of the *Philosophical Transactions of the Royal Society* a valuable contribution. He noticed that fatigue was able to produce slow yielding whenever the compressive and tensile stresses were not equal, even though the maximum stress applied was considerably below the yield stress.

Time Effect.—If a mild-steel specimen be tested up to just beyond its elastic limit, and, after removing the load, allowed to stand, it will be found to recover its elastic properties with time, and on again testing, the elastic break-down point will be found to be raised.

Effect of Low Temperature Heat Treatment.—This same recovery of elastic properties is even more marked if the

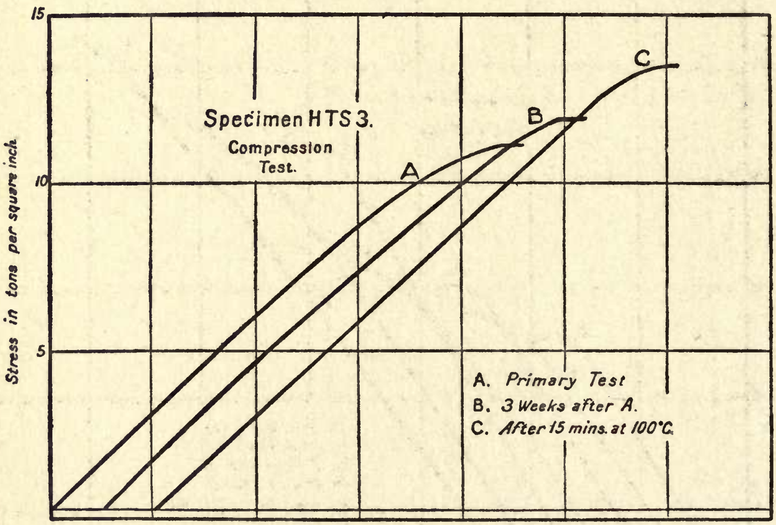


FIG. 67.—Effect of Time and Boiling on Mild Steel Specimen in Compression.

specimen be boiled at 100° C. for a short time. Both time and heat treatment effects are shown in Fig. 66. The specimen was a sample of high tenacity steel of remarkably uniform properties. The data in connection with the method of treatment is given on the curve. A similar phenomenon is observed both in compression and tension tests. Fig. 67 shows a typical curve obtained with mild steel in compression.

Effect of High Temperature Heat Treatment.—This phenomenon is discussed in Appendix IV. The curves shown in Fig. 68 are those obtained from the same material but subjected to various high temperature heat treatments. It

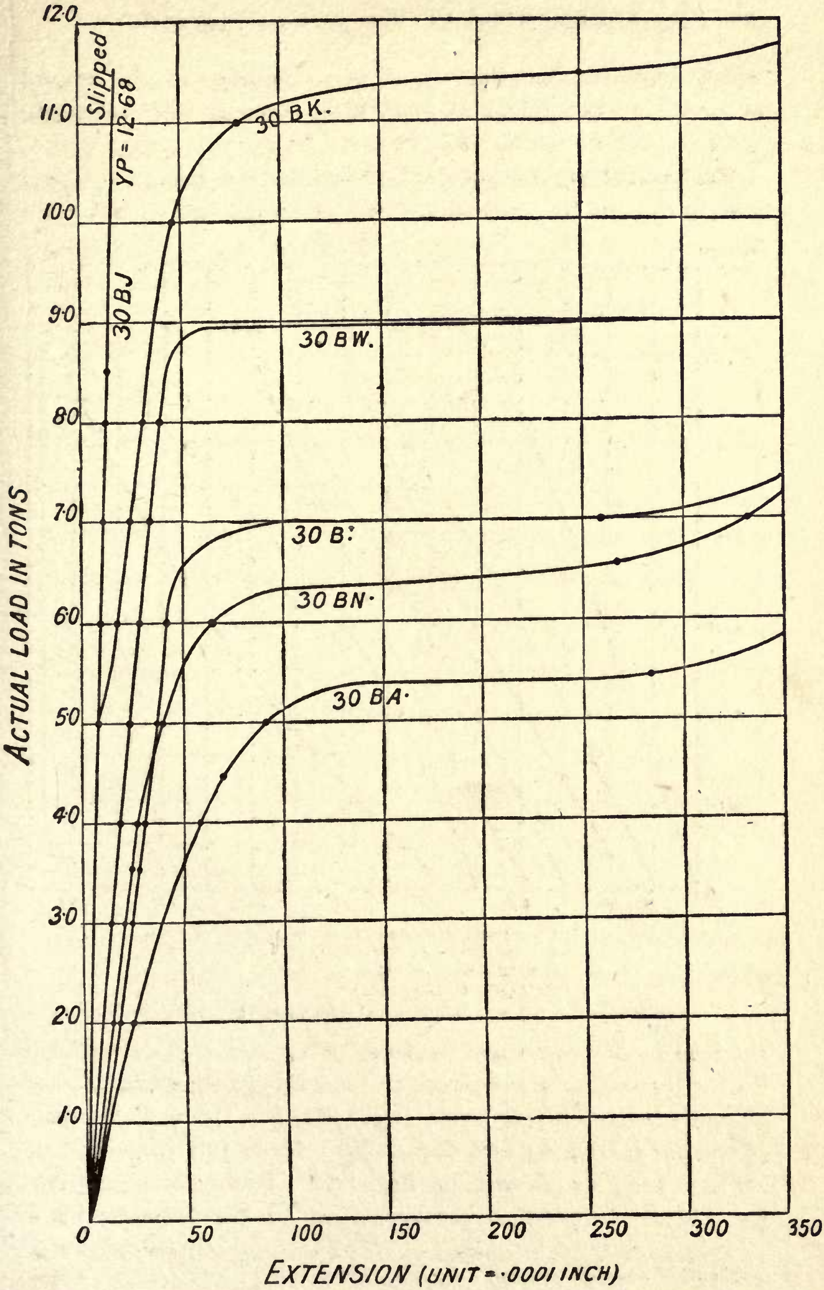
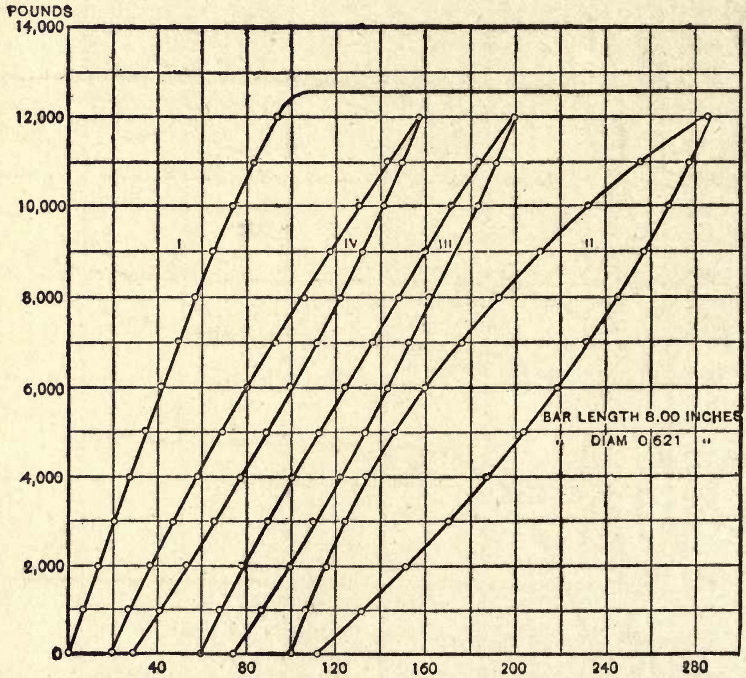


FIG. 68.—Curves showing Effect of Heat Treatment on Bessemer Steel.

will be observed that there is a great change in the elastic properties of the Bessemer steel thus treated. References to the tests will be found on p. 260.

Mechanical Hysteresis.—If a specimen be loaded up past a certain point (in general below the elastic limit) and then



I - ORIGINAL STRESS-STRAIN CURVE, DEC. 7TH 1901.
II - IMMEDIATELY AFTER NO. 1.
III - JANUARY 15TH 1902
IV - FEBRUARY 23RD 1902

FIG. 69.—Curves showing Mechanical Hysteresis.

the load be decreased and readings of extension be taken both during increasing and decreasing load we get the phenomenon known as mechanical hysteresis. That is to say, the two curves for increasing and decreasing load do not coincide but enclose area as shown in Fig. 69. Professor Coker has made many interesting researches on this phenomenon,[1] and

[1] On the effect of low temperature on the recovery of overstrained iron and steel. *Physical Review*, Vol. XV., 1902.

the curves reproduced are from some of his results obtained on mild steel. His object was to determine the effect on mechanical hysteresis of time. It will be seen on comparing the curve in Fig. 69, and the data given immediately below it, that the effect of time is to increase the hysteresis. This hysteresis is probably due to friction between the particles of the metal moving relative to one another under strain.

Further data as to the effect of time, etc., will be found on consulting the proceedings of the engineering institutions. Some curves are also given in Chapter VI. showing these phenomena as exhibited with torsion specimens.

Modulus of Elasticity, E.—The modulus of elasticity, or Young's Modulus is the ratio of stress to strain within the elastic limit. Suppose a specimen be tested to the elastic limit and by some means a curve is obtained with the extensions of the specimen as abscissæ, and the loads causing these extensions as the ordinates.

$$\text{Now } E = \frac{\text{stress}}{\text{strain}} = \frac{\dfrac{\text{load}}{\text{sectional area of bar}}}{\dfrac{\text{extension}}{\text{original length}}}$$

$$= \frac{\text{load}}{\text{extension}} \times \frac{\text{original length}}{\text{sectional area}}$$

$$\therefore E = \text{slope of the load-strain line multiplied by a constant.}$$

From which simple equation E can be found.

The load-strain, or as it is somewhat loosely called, the stress-strain line, is obtained by some form of extensometer.

For such work round specimens are almost invariably used, as they can be turned and measured very accurately.

The Experiment to Find the Value of E.—The specimen is marked off for the reception of the extensometer, the gauge length and cross-sectional area being accurately determined.

The extensometer is then clamped on to the specimen, the latter being placed in the testing machine, and a small load applied to steady the whole. The load is then run on in equal increments, measurements of the extensions of the specimen being taken in each case by the extensometer.

When the maximum load is reached, the load is reduced by equal decrements, readings of the extensometer being taken as before.

A curve is then plotted between the loads and extensions, both for ascending and descending values of the load, Such curves for mild steel are shown in Fig. 70. The curves are straight lines, proving that within the elastic range the stress is proportional to the strain.

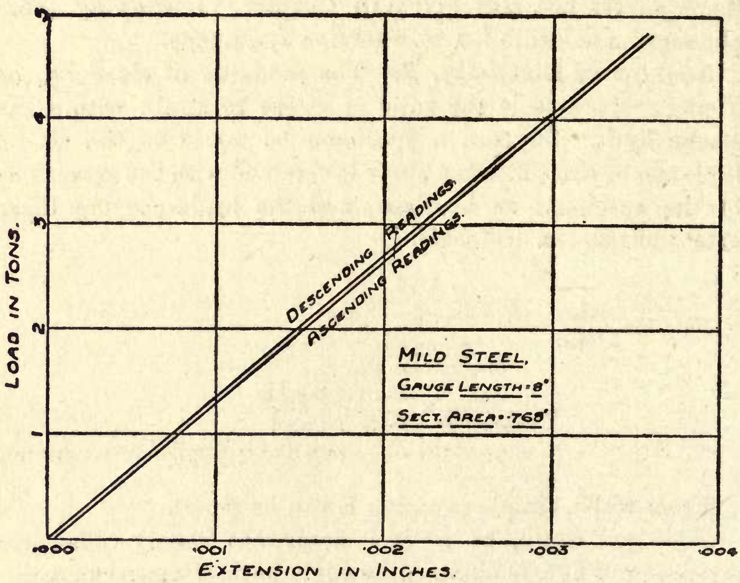


FIG. 70.—Mild Steel in Tension.

The slope of curves $= \tan\theta = \dfrac{4{\cdot}8}{{\cdot}00357} = 1{,}345$ inch ton units.

The cross-sectional area of the specimen $=$ ·768 sq. in.

The gauge length $=$ 8 inches.

$\therefore\ E = 1{,}345 \times \dfrac{8}{{\cdot}768} = 14{,}000$ tons per sq. in., or 31,400,000 lbs. per sq. in.

The following tests were made with the Ewing extensometer, and the tables indicate how results of such tests should be set out.

Specimen I.—Brass Rod.

Observations.

Distance between gauge marks on specimen, 8 inches.
Leverage of machine, 22·4.
Value of 1 division on microscope scale, 0·0002.
Diameter of specimen, ·3755, ·375, ·375 inches.
Mean diameter of specimen, ·375 inches.

Load. Lbs.	Reading on Scale. (Loading.)	Readings on Scale. (Unloading.)	Extensions. Inches.
10	21	21	·0010
20	26	26	·0011
30	32	31	·0009
40	36	36	·0011
50	42	41	·0010
60	47	46	·0010
70	52	51	·0010
80	57	56	·0010
90	62	61	·0013
95	68	68	
85	Totals.		·0094

Specimen II.—Hard Steel Rod.

Observations.

Distance between gauge marks on specimen, 8 inches.
Leverage of machine, 22·4.
Value of 1 division on microscope scale, 0·0002 inches.
Diameter of specimen, ·358, ·356, ·356 inches.
Mean diameter, ·357 inches.

Load. Lbs.	Reading on Scale. (Loading.)	Reading on Scale. (Unloading.)	Extensions. Inches.
10	28	28	·0006
20	31	31	·0006
30	34	34	·0006
40	37	37	·0006
50	40	40	·0006
60	43	43	·0006
70	46	46	·0006
80	49	49	·0006
90	52	52	·0003
95	53·5	53·5	·0003
100	55	55	
90	Totals.		·0054

Specimen III.—Mild Steel.

Observations.

Distance between gauge marks on specimen, 8 inches.
Leverage of machine, 22·4 inches.
Value of 1 division on microscope scale, 0·0002.
Diameter of specimen, ·374, ·374, ·374 inches.
Mean diameter, ·374 inches.

Load. Lbs.	Reading on Scale. (Loading.)	Reading on Scale. (Unloading.)	Extensions. Inches.
10	3·9	3·75	·00055
20	4·2	4·00	·00055
30	4·4	4·35	·00070
40	4·8	4·65	·00060
50	5·1	4·95	·00045
60	5·25	5·25	·00040
70	5·4	5·5	·00060
80	5·7	5·8	·00050
90	6·0	6·0	·00070
100	6·35	6·35	
90	Totals.		·00505

Specimen IV.—Wrought-Iron Rod.

Observations.

Distance between gauge marks on specimen, 8 inches.
Leverage of machine, 22·4.
Value of 1 division on microscope scale, 0·0002 inches.
Diameter of specimen, ·381, ·389, ·385 inches.
Mean diameter, ·385 inches.

Load. Lbs.	Reading on Scale. (Loading.)	Reading on Scale. (Unloading.)	Extensions. Inches.
10	28	28	·0005
20	31	30	·0005
30	33	33	·0006
40	36	36	.0004
50	38	38	·0006
60	41	41	·0005
70	43·5	43·5	·0005
80	46	46	·0005
90	48·5	48·5	
80	Totals.		·0041

COLLECTED RESULTS OF EXPERIMENT TO FIND THE VALUE OF YOUNG'S MODULUS.

Specimen Number.	Load × Leverage.	Area.	Length.	Extension.	Strain.	Stress.	E.
	lbs.	sq. in.	inches.	inches.		lbs. sq. in.	lbs. sq. in.
1 .	1,904	·111	8	·0094	·00118	17,190	$14·55 \times 10^6$
2 .	2,017	·101	8	·0054	·00063	20,000	$29·4 \times 10^6$
3 .	2,017	·110	8	.00505	·00063	18,310	$29·1 \times 10^6$
4 .	1,791	·117	8	·0041	·00051	15,350	$30·1 \times 10^6$

Determination of the Modulus of Elasticity by Bending.—The value of the modulus of elasticity can also be obtained by the method of bending. Suppose, for example, it is required to find E, for a wrought-iron girder.

The testing machine is arranged so that the girder to be tested is placed across the knife-edges, which are fixed a definite distance apart. The load is then applied in the usual way to the specimen by the central knife-edge, the maximum deflection being read by a microscope and scale affixed to the girder.

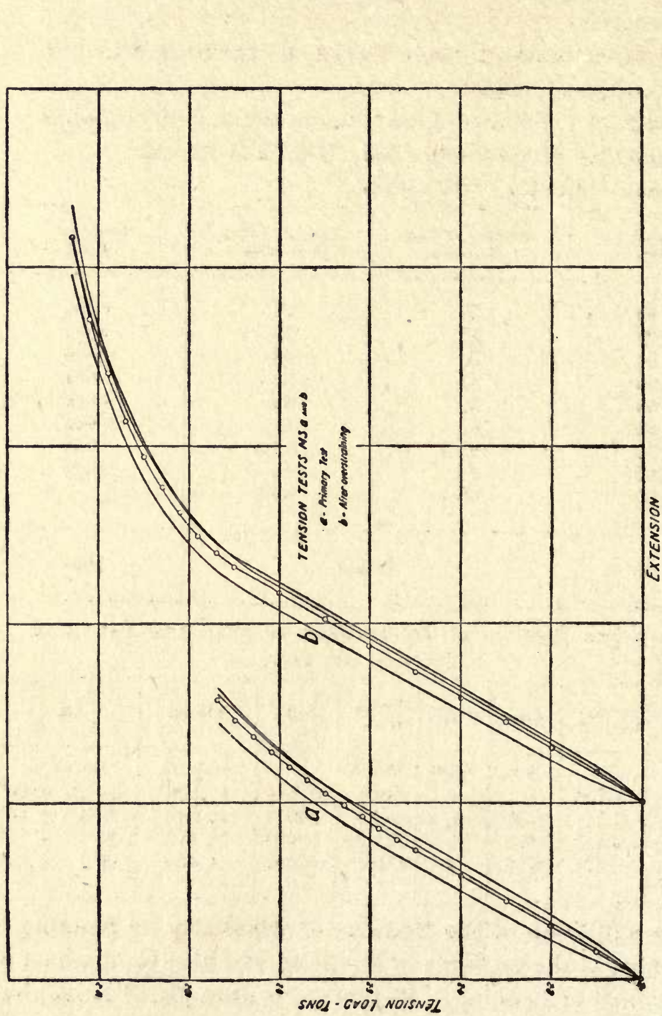


FIG. 71.—Tension Tests on Muntz Metal Specimens show that there is a very considerable "Elastic Limit" Effect with this Material. It is made more elastic by overstrain. The Smooth Lines are the Three Stress Curves obtained by the Sphingometer.

TENSION TESTS ON MUNTZ METAL. SPECIMEN (M3*a*). FOR CURVES, SEE FIG. 41.

Diameter=1·000 inch. Length between gauge-points=3·46 inches.

Calibration of Strips:—

I. 1 Scale Division=0·0000219$_2$.
II. 1 Scale Division=0·0000285$_7$.
III. 1 Scale Division=0·0000273$_1$.

Date of Test, 13/7/09.

Load in Tons.	Strip I.			Strip II.			Strip III.			Mean Extension in Inches, × 10³.
	Scale Reading.	Extension in Scale Divisions.	Extension in Inches, × 10³.	Scale Reading.	Extension in Scale Divisions.	Extension in Inches, × 10³.	Scale Reading.	Extension in Scale Divisions.	Extension in Inches, × 10³.	
0·2	115	0	0	105	0	0	179	0	0	0
1·2	139	−24	−0·526	67	38	1·09	116	63	1·72	0·761
2·2	132	−17	−0·372	33	72	2·06	77	102	2·79	1·493
3·2	113	2	0·044	4	101	2·89	45	134	3·66	2·198
4·2	85	30	0·658	− 26	131	3·75	20	159	4·35	2·919
5·2	54	61	1·335	− 55	160	4·57	− 5	184	5·03	3·645
5·6	42	73	1·600	− 67	172	4·92	− 14	193	5·28	3·933
6·0	29	86	1·883	− 79	184	5·25	− 25	204	5·58	4·238
6·4	16	99	2·170	− 93	198	5·66	− 36	215	5·88	4·570
6·8	3	112	2·450	−107	212	6·06	− 47	226	6·17	4·893
7·2	− 10	125	2·730	−121	226	6·46	− 58	237	6·49	5·227
7·6	− 24	139	3·040	−137	242	6·92	− 70	249	6·81	5·590
8·0	− 38	153	3·350	−153	258	7·38	− 82	261	7·13	5·953
8·4	− 53	168	3·680	−170	275	7·86	− 96	275	7·53	6·357
8·8	− 68	183	4·010	−190	295	8·44	−111	290	7·93	6·793
9·2	− 87	202	4·420	−210	315	9·00	−126	305	8·34	7·253
9·6	−108	223	4·880	−235	340	9·72	−144	323	8·89	7·830
Load removed to find Permanent Set.										
0·2	38	77	—	67	38	—	185	−6	—	—

A succession of readings are taken for loads varying from zero to a load well within the elastic limit, and a curve plotted with the deflections as abscissæ, and the loads as ordinates. The deflection of a bar supported at the ends and loaded centrally is given by the expression

$$y=\frac{Wl^3}{48EI}.$$

y = Deflection.
W = Load applied.
l = Distance between knife-edges.
E = Modulus of elasticity.
I = Moment of inertia of the cross-section of the girder,

from which

$$E=\frac{W}{y}\cdot\frac{l^3}{48I}$$
$$=\frac{l^3}{48I}\times\text{slope of load-deflection curve.}$$

The cross-sectional dimensions of the girder are taken, and the moment of inertia calculated. A simple method of obtaining a diagram of the section is to smear the latter with red lead, and obtain an impression of it on a piece of paper.

The distance between the knife-edges is known, and the slope of the load-deflection line measured, and consequently E can be calculated.

Approximate values of E for different materials:—

Material.	E. Lbs. per sq. in.[1]
Cast-iron	17,000,000
Wrought-iron bars	29,000,000
Steel boiler plates	30,000,000
Steel plate (mild)	31,000,000
Cast-steel (untempered)	30,000,000
Copper rolled plate	15,000,000
Brass	13,500,000
Gun-metal or bronze	13,500,000
Phosphor bronze	14,000,000
Wood (pine)	1,600,000
Wood (oak)	1,450,000

[1] Unwin's Machine Design, Part I.

The values of the moduli must necessarily depend on the qualities of the materials, so that the values given above must only be taken as approximate.

Testing with the Sphingometer.—As explained briefly in Chapter IV., page 66, the Sphingometer can be used, not only to determine direct extensions, but also to determine the stress distribution in the specimen. Normally one measures the extension in three planes at 120° and the mean value of these three measurements is used for the calculation of E. The Table on page 113 shows how the readings are set out and calculated. If the readings of each strip be plotted separately we obtain the irregular curves shown in Fig. 71. The mean curve, however, in the case of an elastic specimen is straight. This latter line gives all the necessary information for obtaining the value of E, etc., while the separate curves are used to determine stress distribution in the manner explained in Appendix III., page 249, where a test on mild steel is worked out. The readings taken in three planes demonstrate that the load does not pass through the axis of the specimen. It is especially interesting to test a specimen, and obtain readings with the instrument, with Vee-grips in the testing machine.

CHAPTER VI

TORSION TESTING

Brittle Materials in Torsion.—When brittle materials, such as cast-iron, are subjected to torsion, a fracture, usually almost perfect in form, results. It is inclined roughly at an angle of 45° to the axis of the specimen, and makes a complete revolution of the bar, the junction of the ends of the spiral being approximately a straight line. The theoretical line of fracture is illustrated in Fig. 72. Fig. 73 shows a

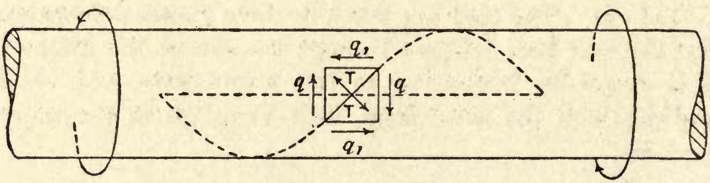


Fig. 72.—Cast-Iron under Torsion.

drawing of a hollow specimen fractured in torsion, and photographs of actual fractures are shown in Plate III. It can be readily seen why rupture occurs in this peculiar way if an elementary square on the surface of the specimen be considered.

The torque on the specimen introduces shear forces q (Fig. 72) on the faces of the elementary square as shown. But as equilibrium is maintained, it is evident that there must be equal and opposite shear forces q on the other two faces It can now be readily proved that this brings into action a tensile stress of equal intensity on the face inclined to the others at 45°.

Now, cast-iron is weaker in tension than in compression or

shear, and will consequently give way along that surface where the stress is tensile.

If this tensile stress be calculated, it will be found to approximate closely to the breaking stress found by pure tension. The calculation is performed as follows:—

Twisting moment $= q$ Z.

Where $q =$ shear stress produced

Z $=$ modulus of the section.

But Z for a round bar $=\frac{\pi d^3}{16}$

$$\therefore q=\frac{16\times \mathrm{TM}}{\pi d^3}$$

but tensile stress $f_t=q$

$$\therefore f_t=\frac{16\times \mathrm{TM}}{\pi d^3}.$$

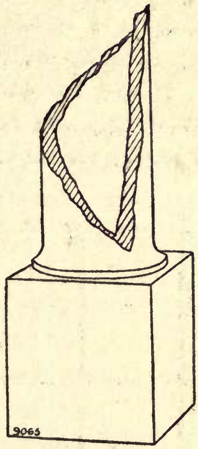


FIG. 73.—Fracture of Cast-Iron Hollow Specimen in Torsion.

The following results were obtained from hollow cast-iron specimens :—

No. of Specimen.	Internal Diameter.	External Diameter.	Torque. Internal lbs.	Tensile Stress. Lbs. per sq. in.	Angle of Fracture. Internal.	Angle of Fracture. External.
1	·904	1·289	6,020	19,000	45½°	49½°
2	·892	1·125	2,920	17,500	45°	49°
3	·990	1·249	3,180	13,850	47°	45°

Ductile Materials.—The behaviour of ductile materials in torsion is very different from that of brittle materials. The specimen twists considerably and fracture, being due to shear, takes place in a plane approximately perpendicular to the axis.

Fig. 74 shows a load-strain curve plotted for mild steel.

As the angle through which the specimen twists is large, it can be obtained sufficiently accurately, as explained later[1], by observing the number of turns of the hand-wheel actuating the torque. Then, knowing the number of teeth on the wheels brought into play, the angle of twist can

[1] See description of the Bailey machine, page 119.

be calculated. The actual readings of the mercury column are plotted as ordinates. Then since the torque arm in this case is 4 inches long, the torque on the specimen can be obtained by multiplying the mercury column readings by four.

It will be observed that the diagram is not dissimilar to those obtained from tension or compression tests. There is first the elastic period, giving a straight line, then a distinct

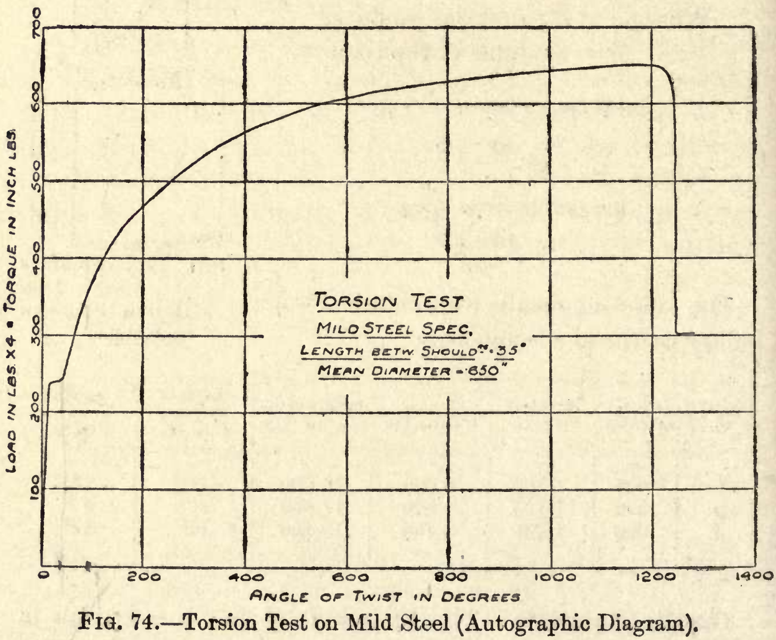


FIG. 74.—Torsion Test on Mild Steel (Autographic Diagram).

yield point, followed by a curve of the shape usually met with in autographic diagrams. Mild steel being a very ductile material twists considerably before rupture, and the curve shows a total twist of 1250 degrees.

Wrought-iron exhibits the same characteristics, though not to so large an extent, although the cracks and markings are much more noticeable.

Gunmetal breaks more quickly, the surface presenting a a very uneven and blotched appearance, owing to the effects

of compression in some places and tension in others, as shown in Fig. 75.

Tests on cast-steel show that its behaviour is intermediate between that of cast-iron and the ductile metals, approaching more nearly to either extreme according as the steel is hard or soft.

Torsion Testing Machines.

The "Bailey" Torsion Machine (Fig. 76).—The specimen consists of a cylindrical bar with enlarged ends, which are either of square section or are fitted into square caps by means of keys. The object of the test is to find the resistance of the bar to torsion or twisting, so that it is not necessary to grip the bar tightly in the clips, but only to prevent it from rotating in them. In fact, it is necessary to allow the bar to slide a little longitudinally, as when twisted it becomes rather shorter than before. Two views of the machine are shown in Fig. 76. The end A_1 of the bar is twisted by means of the hand-wheel B, which turns the worm-wheel C. This in its turn rotates the spur-wheel D, to which the grip A_1 is rigidly attached. The other end of the bar, held in the clip A_2, attempts to turn with A_1, and with that intent pulls at the lever E, which is connected by the tie rod G to the mercury diaphragm[1] F. The pressure on this diaphragm

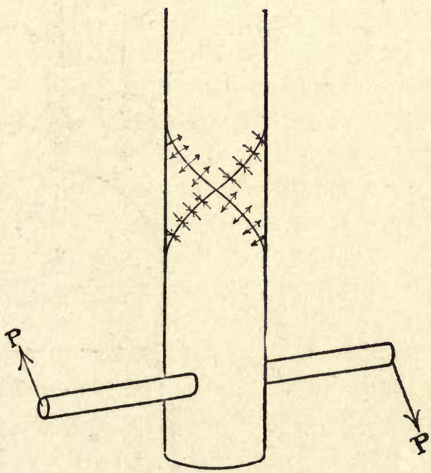


Fig. 75.—Stresses induced in a Bar subjected to Pure Torsion.

[1] In the usual type of machine this diaphragm is made of rubber. Prof. Hummel states that he finds a great improvement by substituting a thin brass diaphragm in this machine.

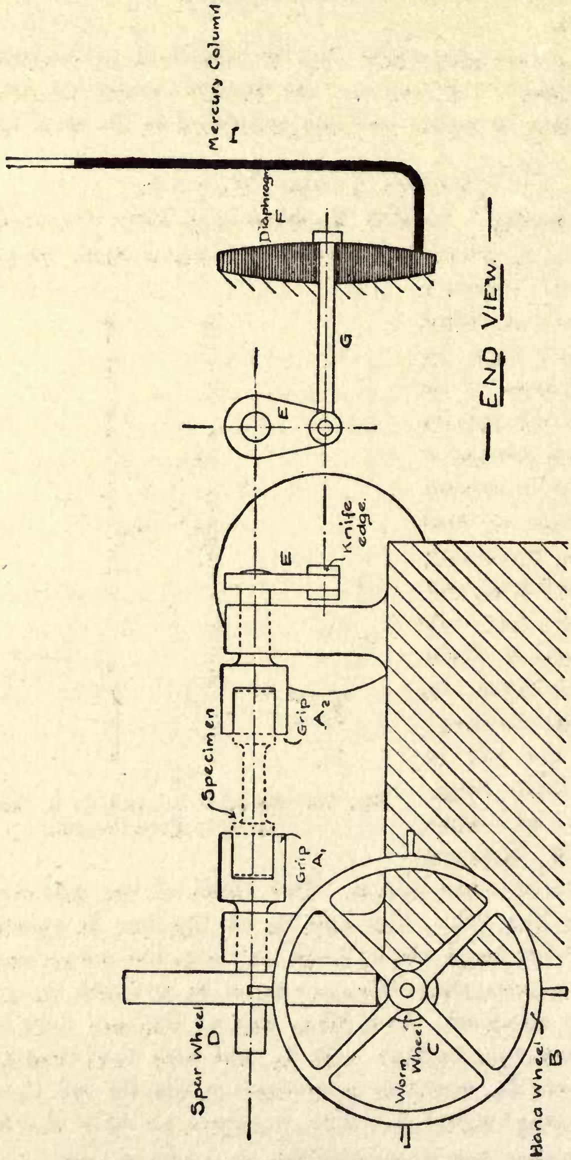


FIG. 76.—Bailey Torsion Testing Machine.

causes the mercury to rise in a column H, which balances the pressure due to the tie rod G. Thus the height of the column H gives a measure of the torque or twisting force exerted on the specimen. The mercury column is calibrated to give the tension in the tie road G, and, since the length of the arm E is known, the torque on the specimen is easily found.

"Thurston" Torsion Machine.—In this machine the load is applied in the same way, but the method of measurement is different. A pendulum weight is affixed to the free end of the test bar, and, as the load is applied, the test bar is able to move this pendulum through a distance proportional to the load. The pendulum, therefore, is caused to move a pointer along its quadrant, the latter being calibrated to read the load on the specimen. When the bar breaks, the pendulum swings back into a vertical position, but the pointer remains in the position that it had assumed just before the specimen broke. The final position of the pointer, then, gives us the breaking torque on the test bar.

"Avery" Torsion Machine.—The Avery machine also has its load applied in the same manner as the Bailey and Thurston machines, viz., by a worm and worm-wheel, but, again, the method of measurement is different. The stress is indicated by means of a system of weighing levers, similar to those in the Riehlé testing machine, being finally measured by running out a poise along a graduated steelyard. In the 15,000-inch lb. machine there are three of these poises, each weighing 60 lbs. The first indicates up to 5,000 inch lbs., when each scale division on the steelyard represents $\frac{1}{2}$ lb. When two poises are coupled together readings can be taken up to 10,000 inch lbs., and when the whole 180 lbs. are run along the scale they give a total capacity of 15,000 inch lbs., with readings of 5 inch lbs. per scale division. A vertical scale is sometimes fixed on the front end of the steelyard, and a telescope to the frame of the machine. By this means we can adjust the lever with great accuracy until it rests in a perfectly horizontal position. This machine will take square bars up to $\frac{7}{8}$ inch side, or rectangular specimens up

to a maximum size of 1 inch × $\frac{3}{4}$ inch. The bracket on which the straining gear is fixed is capable of movement to admit specimens of a maximum length of 15 inches. The shortening of the specimen under the torsional load is provided for by the insertion of hardened steel rollers. The actual strain on the specimen is observed by fastening indicating arms to its two ends a gauge length apart. These arms are in line with each other at the start, but as the load is applied one end gets twisted more than the other, so that the angle between them at a definite load gives us the torsional strain at that load.

This machine is also arranged to measure a torsional stress applied in the reverse direction. The main torsion lever T is keyed on a sleeve which is free to revolve in ball bearings. An intermediate lever R is arranged within this main lever, and is pivoted at a point G between the axis of the specimen and that of the tension rod which transmits the stress to the steelyard. When the torsion is applied in a clockwise direction, the knife-edge C of the main lever pulls up the left hand end of the intermediate lever, and so depresses the end that is attached to the tension rod. When the stress is applied in a contra-clockwise direction, the knife-edge K raises the point E of the intermediate lever, and again pulls the tension rod downward. So that, in whatever direction the torsional load is exerted, the short end of the steelyard is always pulled downward, balance being restored by running the poise along the arm. The leverages are so arranged that the load on the specimen, in either direction, can be read directly on the same scale.

The same makers also manufacture a testing machine to give results in tension and torsion simultaneously, so that the effect of the combined stresses can be read off in one machine. It consists practically of a hydraulic tension machine and a hand-power torsion machine on the same bedplate. The principles upon which the combined machines act are similar to those already given for the separate machines. A detailed account of the tension-torsion tester

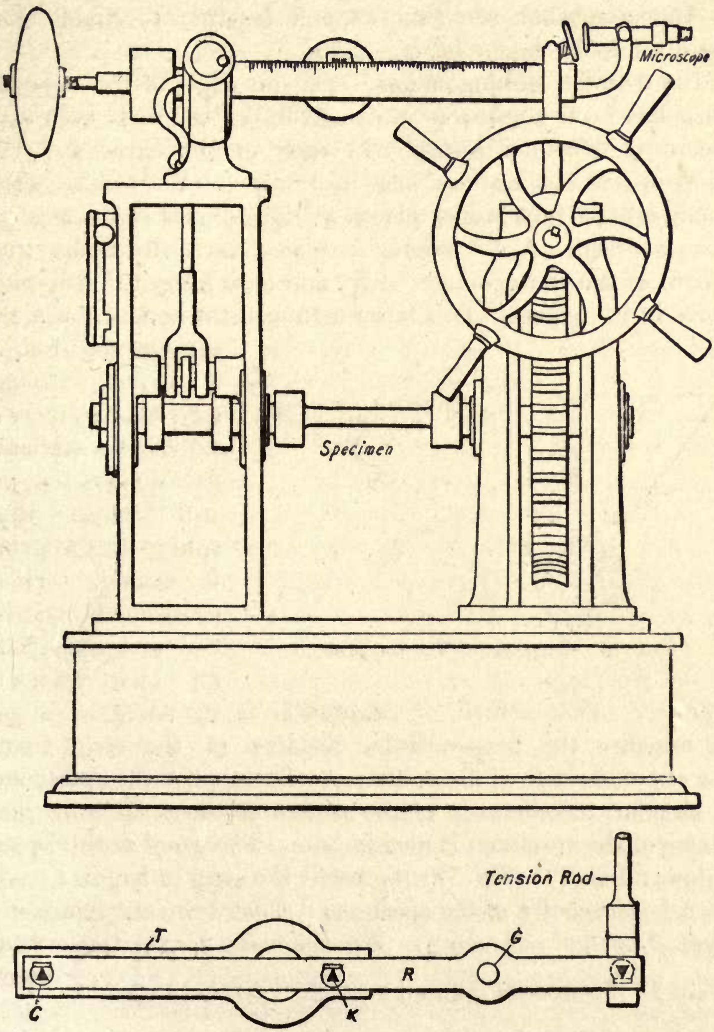


Fig. 77.—Hand-Torsion Testing Machine.

is given on page 251. The two steelyards, one for each kind of stress, are placed so that neither interferes with the working of the other, but are near enough together to enable the readings to be taken by one man.

The Torsion Sphingometer.—The principle of the twisted strip has been applied to the instrument which is used for recording torsion strains. To each of the carriers "C" (Fig. 40) is fastened an arm carrying a "V" block. The sphingometer tube is now placed at right angles to the axis of the specimen. A 45° mirror is placed vertically under the mirror of the sphingometer strip, and is so hinged that it will move in two planes. This latter arrangement makes it easy to arrange for illuminating both mirrors. Any movement of the carriers "C" due to a torque will cause the sphingometer strip to extend. This extension is magnified and recorded in the usual manner. The method of calibration is by using a gauge to measure the perpendicular distance of the strip from the circumference of the specimen. Then since the specimen is circular, the distance of the centre of the strip from the centre of the specimen is also known. The proof of this is as follows: Let B C (Fig. 78) represent the strip of length l, and let A be the centre of the specimen. Then from the figure we have $l^2=c^2+b^2-2bc\cos A$. Whence $2ldl=2bc\sin A dA$. But

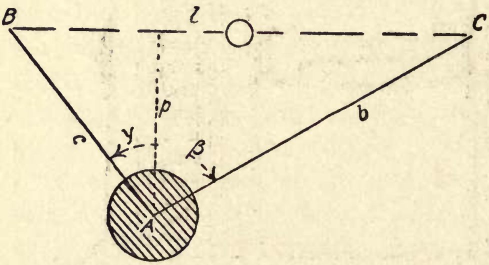


FIG. 78.—Diagram of Torsion Meter.

$$bc\sin A=2\times\text{area of triangle}=pl.\quad\therefore\ dl=\frac{pl}{l}dA=pdA.$$

Hence it is obvious that in order to measure the angular displacement the only necessary measurement is that of the perpendicular to the strip from the centre of specimen. This can be obtained very accurately by means of a gauge. In

Fig. 40 the three strips used for measuring strains in a tension or compression test are shown, and also the torsion strip is in position. It may be mentioned that the position of this strip can be readily altered if it is desired to use short distances between the gauge-points. Lever arms may be fastened to both carriers, and the torsion V-block secured to the lever arms. This also increases the sensitiveness of the strip. It has the further advantage that the perpendicular distance p is measured with greater accuracy. A torsion test

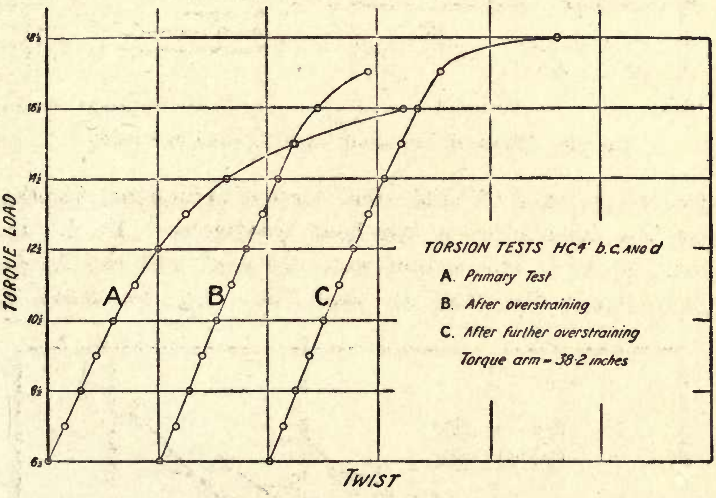


FIG. 79.—Effect of Overstrain in Torsion (Mild Steel Specimen).

and the curve obtained with a copper specimen is given above. For a description of a very excellent torsionmeter, devised by Prof. Coker, see page 258.

Typical Results of Torsion Tests.—In Fig. 74 we showed a typical curve for a torsion test when carried up to fracture, but many of the most interesting torsion experiments are performed with stresses which only slightly exceed the elastic limit.

Effect of Overstrain.—On page 103 a brief explanation of this phenomenon was given as it appears in the case of tension and compression specimens. Figs. 79 to 83 illustrate the

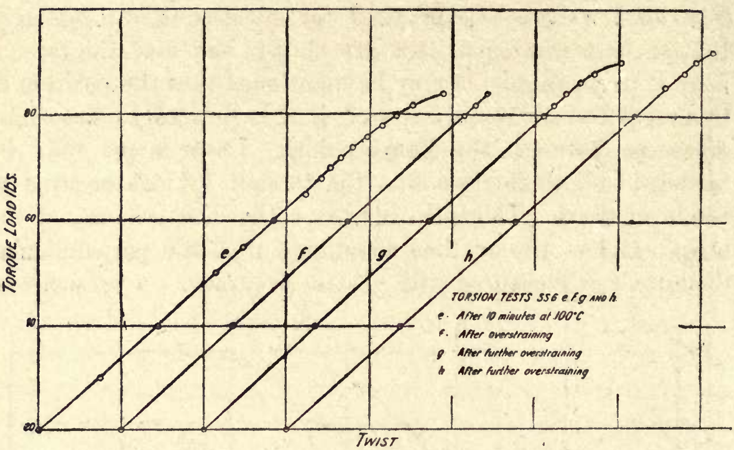


FIG. 80.—Effect of Overstrain on Mild Steel in Torsion.

effect in the case of mild steel torsion specimens, together with the allied effect of **low heat treatment.** All the diagrams given in this section were obtained with the torsion sphingometer described on page 124. Fig. 84 shows yet

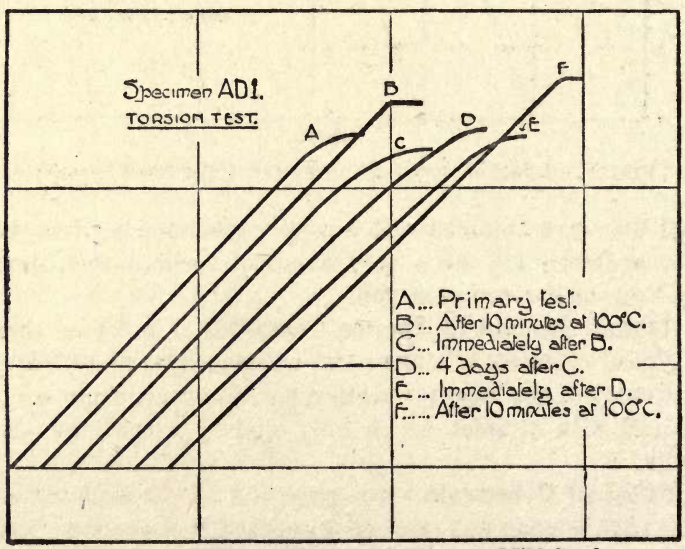


FIG. 81.—Effect of Time and Boiling on Mild Steel.

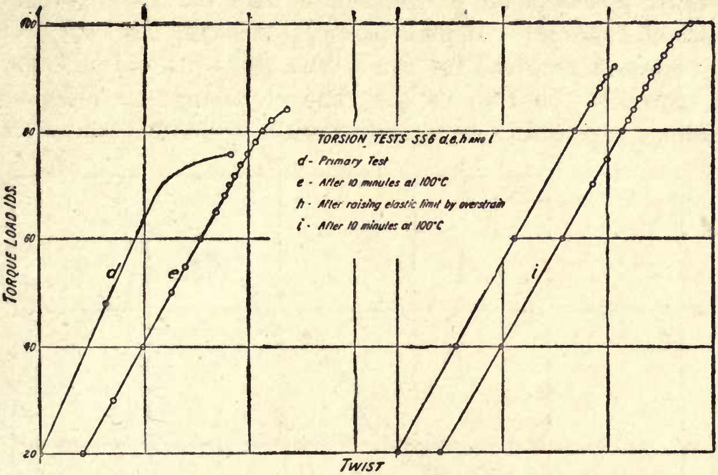


FIG. 82.—Effect of Overstrain and Boiling on Mild Steel in Torsion.

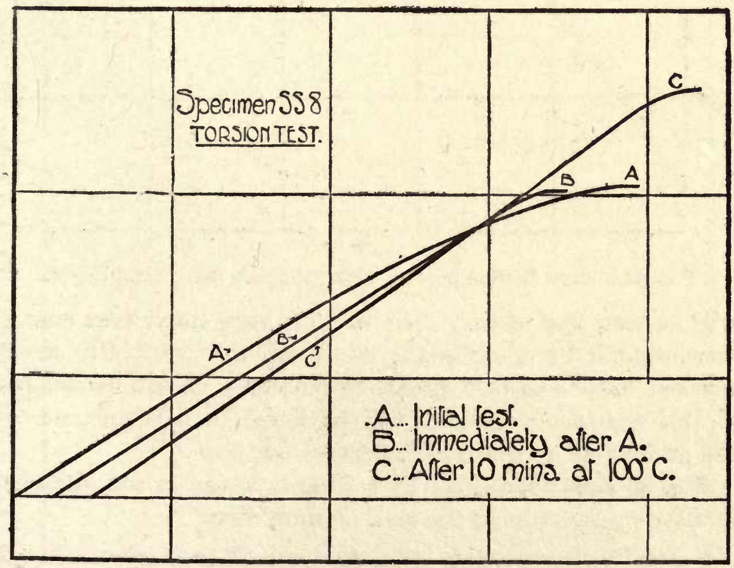


FIG. 83.—Effect of Overstrain and Boiling on Mild Steel in Torsion.

another phenomenon in connection with the elastic breakdown of materials. If after passing the elastic limit the load be sustained constant for some time, the twist will be found to increase. In Fig. 84 the time of taking the different readings is placed in juxtaposition with the plotted point. It

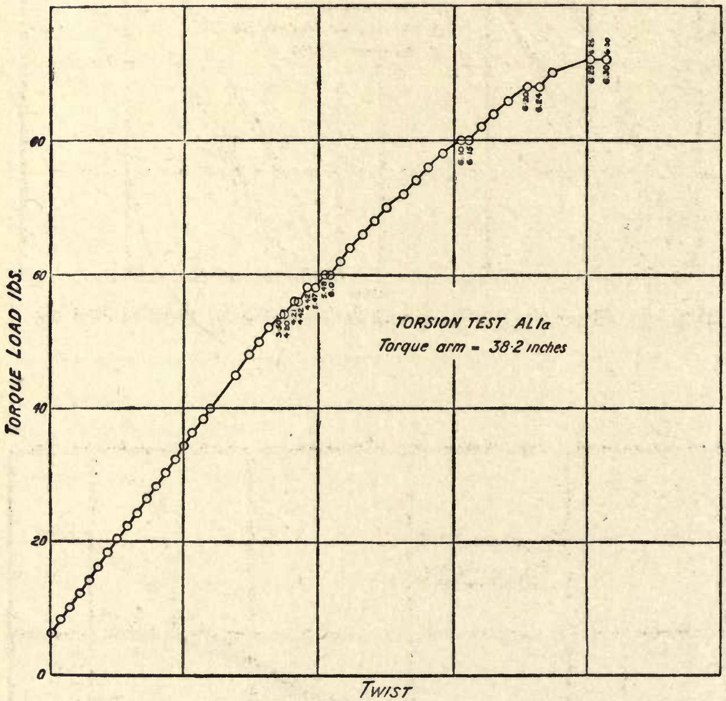


FIG. 84.—Pure Torsion Test on Aluminium showing Time Effect.

will be seen that at first the "slip" is very small even over a considerable time, while the effect becomes gradually more marked until complete breakdown occurs. A full discussion of this gradual breakdown will be found in a paper read by the author before the Iron and Steel Institute.[1]

Fig. 85 shows the effect of boiling in water on the recovery of elastic properties in the case of aluminium.

[1] "The Elastic Breakdown of Certain Steels," *Journal of the Iron and Steel Institute*, May, 1910.

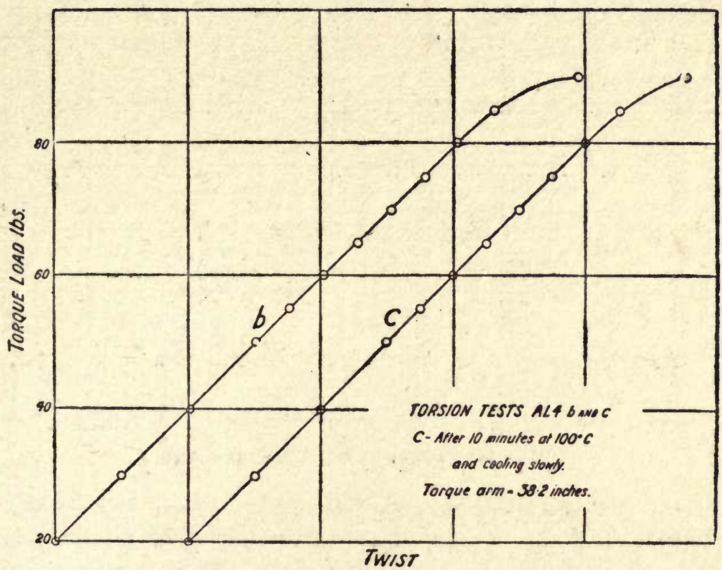


FIG. 85.—Torsion Tests on Aluminium.

Figs. 86 and 87, on copper specimens, will show that normal annealed high conductivity copper has no very marked elastic limit, the curve gradually bending over

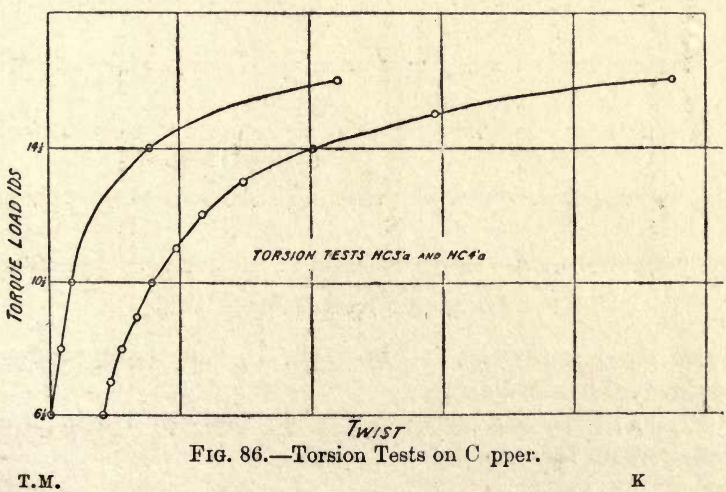


FIG. 86.—Torsion Tests on C pper.

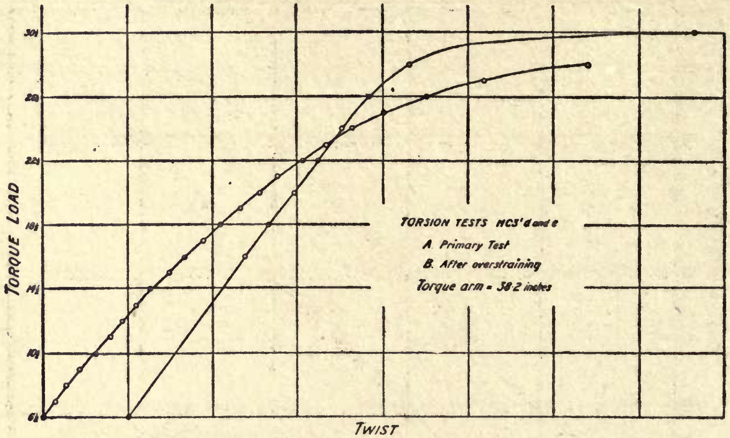


FIG. 87.—Effect of Overstrain on Copper.

After overstraining beyond the elastic limit, a hardening effect takes place, which causes the material to give a curve more closely allied to other materials. The curve obtained

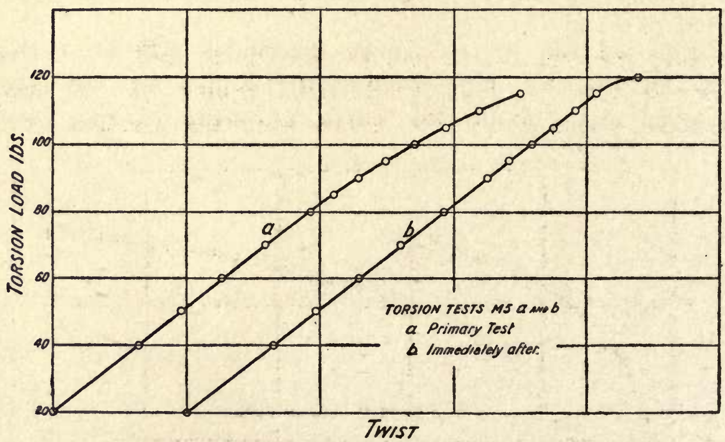


FIG. 88.—Torsion Tests on Muntz Metal.

with the primary test in Fig. 87 is the one starting from a point farthest to the left.

Table IV. and the curves in Fig. 88 show the arrangement of a test on Muntz metal.

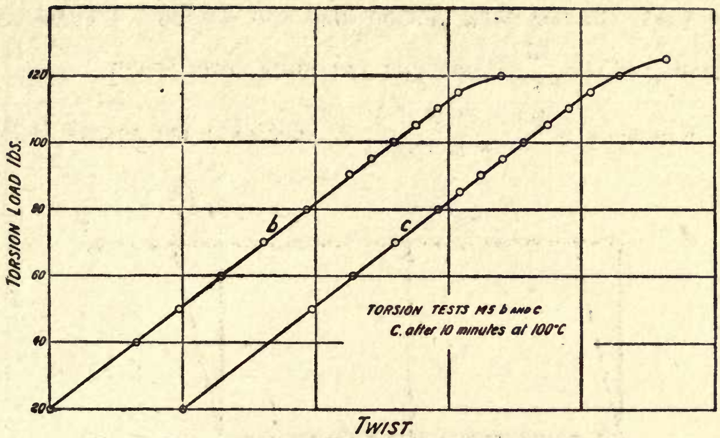


FIG. 89.—Torsion Tests on Muntz Metal.

TABLE IV.—TORSION TEST ON MUNTZ METAL (M5a).
(FOR CURVES, SEE FIG 88.)

Diameter of specimen = 1·000 inch.
Perpendicular distance of strip from centre of specimen = 3·72 inches.
Calibration of strip, 1 scale division = 0·0001080$_0$ inch.

Load in lbs.	Scale Readings.	Scale Differences.	$\frac{1}{100}$ of a Radian.
20	−193	—	0
40	−66	127	0·368
50	−2	191	0·554
60	+61	254	0·737
70	+125	318	0·923
80	+193	386	1·120
85	+228	421	1·220
90	+265	458	1·330
90	−30	Inst^t. reset.	—
95	+10	498	1·445
100	+53	541	1·570
105	+100	588	1·707
110	+152	640	1·857
115	+215	703	2·040

On examining curve 88a, it will be seen that the curve ceases to be straight where load is 85 lbs., whence for the shear stress at elastic limit, the moment of the couple

is T×L (in test M5*a*, T=85 lbs. and L=38·2 inches) we have $q = TL \times \frac{16}{\pi d^3}$, where q is maximum shear stress.

$$\text{Whence } q = \frac{85 \times 38{\cdot}2 \times 16}{\pi \times 1^3} = 16550 \text{ lbs. per square inch.}$$

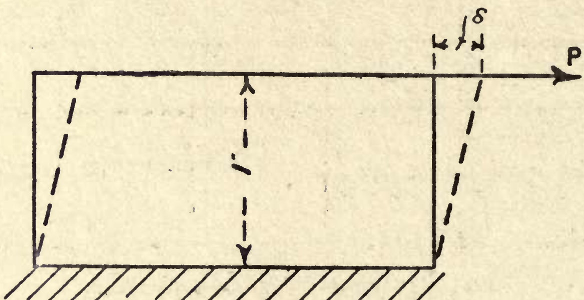


FIG. 90.—Rectangular Block under Shear Stress.

The curve 88*b* is a test on the same specimen immediately after test M5*a*, plotted in Fig. 88*a*.

Fig. 89 shows the effect of overstrain and subsequent boiling on Muntz metal.

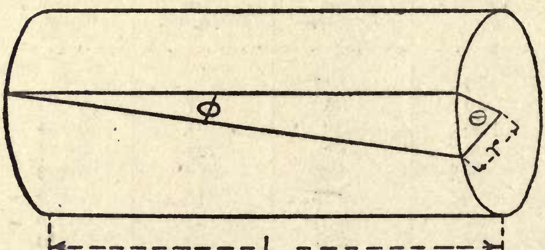


FIG. 91.—Circular Specimen in Torsion.

Modulus of Rigidity C.—The modulus of rigidity C $= \frac{\text{shear stress in lbs. per sq. in.}}{\text{shear strain per inch length}} = \frac{q}{\delta}$.

δ is the strain between two planes an inch apart (Fig. 90).

The simplest method of finding C for any material is by applying a torque to a round specimen and observing the angle of twist over a definite gauge length. This is quite

easily done in the Bailey machine, a torsionometer being used to measure the angle of twist. A succession of readings of twisting moment and angle of twist are thus obtained, both for ascending and descending values of the twisting moment, and a curve plotted with the angles of twist as abscissæ, and the twisting moments as ordinates. Careful measurements are also made of the diameter of the specimen and the gauge length.

Let Fig. 91 represent the specimen of gauge length L, and the radius r.

Let $\phi =$ angle of strain in circular measure, and $\theta =$ angle of twist in circular measure.

$$\text{Then } C=\frac{q}{\phi} \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where $q =$ shear stress produced. But twisting moment, $TM = q\,Z$.

where $Z =$ polar modulus of the section.

$$\therefore q=\frac{TM}{Z}.$$

And since θ, not ϕ, is measured by the torsionometer,

$$L\phi=r\theta$$

$$\phi=\frac{r\theta}{L}.$$

Substitute in (1)

$$\therefore C=\frac{TM}{Z}\times\frac{L}{r\theta}=\frac{L}{Zr}\times\text{slope of stress-strain curve.}$$

All these quantities are known, and consequently C can be calculated.

Approximate values of C for different materials.

Material.	C. Lbs. per sq. in.
Cast-iron	6,300,000
Wrought-iron bars . . .	10,500,000
Steel boiler plate . . .	13,500,000
Cast steel (untempered) . .	12,000,000
Copper rolled plate . . .	5,600,000
Phosphor bronze . . .	5,250,000

Poisson's Ratio.—When a specimen is loaded, there is a direct strain—tensile or compressive, according to the nature

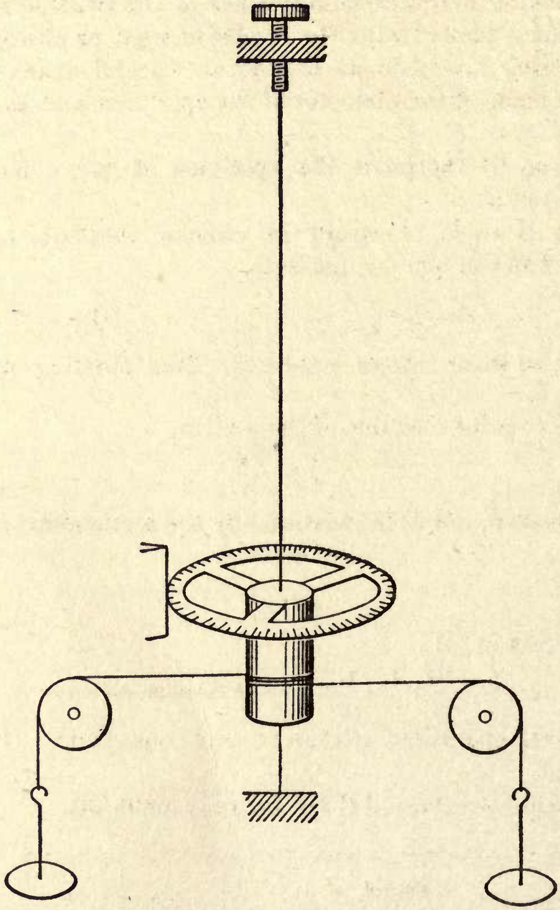


FIG. 92.—Apparatus for Torsion Experiments on Wires.

of the test—and also a lateral strain, the sign of this strain being the reverse of the direct one.

The ratio of the direct strain to lateral strain is known as Poisson's Ratio, and is usually designated by the letter m. As the lateral strain is very small, it is exceedingly difficult to

measure it accurately by direct method. Hence the most usual way is to obtain the moduli of elasticity and rigidity in the manner already stated, and calculate m from the following equation :—

$$m = \frac{E - 2C}{2C}.$$

The following table gives mean values of m for some of the more usual metals :—

Metal.	m.
Cast-iron	3·7
Wrought-iron	3·6
Steel	3·25
Brass	3·0
Copper	2·6

Torsional Experiments on Wire.—The value of the shear modulus can be determined in the case of wires by two methods —(*a*) by static deflection and (*b*) by torsion vibration. Fig. 92 shows the first method in diagrammatic outline. A wire is first pulled taut by being fixed at its lower end and attached to a tightening screw at the top. To the wire is attached a light brass drum carrying a scale divided in degrees. A light cord is passed once or twice round the drum and over two fixed pulleys. To the ends of the cords are attached small scale pans or weight hooks. Equal weights are placed in the scale pans, and the twist of the wire observed by reading the movement of the circular scale relative to a fixed pointer. The twisting movement is, of course, the product of the weight in *one* scale pan into the diameter of the drum. C is obtained from the formula—

$$C = \frac{584\,Ml}{\theta d^4},$$

where M is the twisting movement in lbs. inches, l the length of wire in inches, θ the deflection in degrees, and d the diameter of the wire.

Fig. 93 shows the very simple form of apparatus used to determine C by torsional vibrations. The wire is fixed as before, and carries near its lower extremity a light brass tube. Four other pieces of tube are provided, each exactly one quarter of the length of the long tube, and made to slip inside it. Two of the short pieces are filled with lead, and two are empty. Two values of the time of torsional vibration are obtained—one when the two empty tubes are at the extremity of the long tube, and the other when this order is reversed and the loaded tubes are at the extremities and the empty ones at the centre. It can be shown that

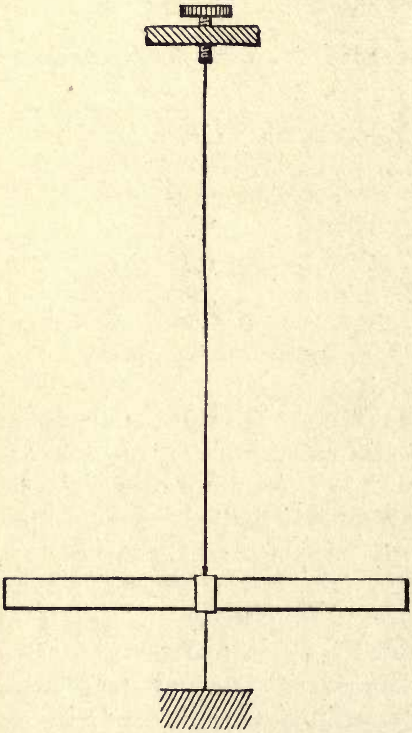


FIG. 93.—Apparatus for Testing Torsional Vibrations of Wires.

$$C=\frac{128\,\pi l}{gd^4}\left[\frac{(m_1-m_2)x^2}{t_1^2-t_2^2}\right].$$

Where C is modulus of torsional rigidity.

l is length of wire in inches.

d diameter of wire in inches.

m_1 mass of each of the tubes filled with lead in lbs.

m_2 mass of each of the empty brass tubes in lbs.

x half the length of the long tube.

t_1 and t_2 the observed times of torsional vibrations, with loaded tubes outside and inside respectively.

CHAPTER VII

IMPACT AND HARDNESS TESTS

THE object of an impact test is to obtain the efficiency of the material on test, when it has to be introduced into a machine or structure where it will be subjected to shocks or suddenly applied loads.

The importance of this branch of testing work is well illustrated in a paper on "Impact Tests" read before the Institute of Mechanical Engineers in 1904 by Messrs. Seaton and Jude, where an approximate analysis of the stresses to which the steel parts of a reciprocating steam engine is given as follows:—

Constant tension	3·91	per cent.
Constant tension and compression (range from O to a maximum) .	1·30	„
Constant tension and shock . .	48·80	„
Alternating tension and compression with shock	2·81	„
Repeat tension (from a constant to a maximum) with shock . .	36·00	„
Miscellaneous and doubtful . .	7·17	„
Total	100·00	

"It will therefore be seen that 87·6 per cent. of the whole of the engine's stresses are more or less due to shock, whilst pure tension stresses form an insignificant percentage of the total stress." It is furthermore stated that if other machines were analysed in a similar manner, nine out of ten would be found to be working under similar conditions.

Avery Machine.—The machine consists of two A frames of

cast-iron, between which swings a pendulum consisting of a steel tube, terminating in a cast-iron head. The specimen, consisting of a small piece of metal $\frac{3}{8}$ of an inch wide and $\frac{3}{16}$ inch in thickness, is placed in a vertical position in a vice at the base of the instrument. The pendulum is then raised to the required height and secured by the releasing trigger carried on the curved arm of the frame. The height to which the pendulum is raised, and consequently its potential energy, is indicated by a pointer on the quadrant at the top of the frame. When the trigger is released, allowing the pendulum to fall and strike the specimen, the indicating pointer engages with a loose registering finger, and carries the latter forward with it. Now if no specimen were present, the pendulum would rise to an equal height on the other side, no energy being absorbed. But when a specimen is broken, the pendulum does not rise so high; its travel on the other side of the vertical, being inversely proportional to the amount of work done in breaking the specimen. Hence the loose registering finger is carried over to the farthest point reached by the pendulum after breaking the specimen, and stays there, thus indicating directly the amount of work done in breaking the test piece. The maximum capacity of this machine is 23 ft. lbs.

Tensile Impact Tester.—The following is a simple machine for examining the properties of materials under tensile impact. The specimen, consisting, let us say, of a long piece of steel wire, is gripped at the upper end in a block which slides upon two or four vertical pillars. The lower end is attached to a heavy hammer-block which keeps the specimen or wire in tension. The whole system is hoisted to some known height up the vertical pillars, and then allowed to fall. In falling, the block which holds the top end of the specimen is suddenly arrested by a stop, fixed to the supporting pillars, while the hammer-block at the lower end is still unsupported. The energy contained in the hammer is arranged to be more than sufficient to rupture the test bar or wire. The actual energy required to just break the specimen is obtained as follows.

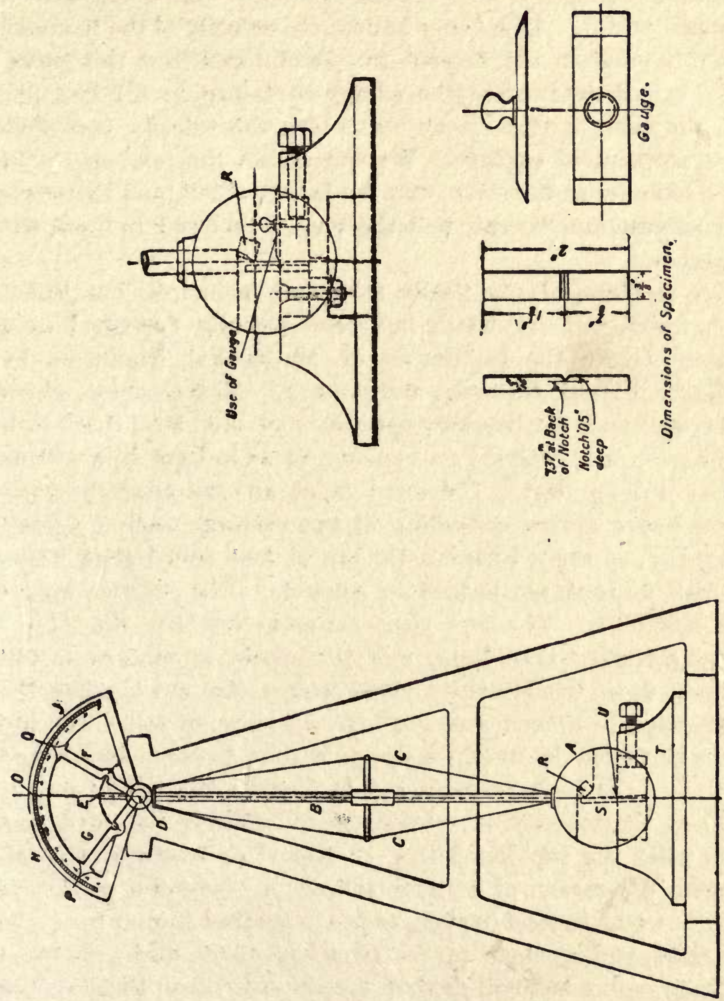


FIG. 94.—Impact Testing-machine.

A rotating drum is provided, and the hammer has a pencil attached to it, which, on falling, describes a time-displacement curve. The surface speed of the drum is found by holding against it a vibrating tuning fork, which has a known period. This being known, the velocity of the hammer at any point in the descent can be obtained from this curve. We can therefore find the energy contained in the hammer at the time of rupture by computing the velocity just after the moment of rupture. We can obtain the total energy in the hammer at the start from the height of fall, and therefore, by subtraction, we can find the energy required to break the specimen.

A machine of identically the same principle, but somewhat different in detail, has been recently described in a paper before the Institution of Mechanical Engineers by Messrs. Blount, Kirkaldy, and Sankey.[1] This machine, which is constructed for breaking specimens of mild steel 0·357 inch diameter, is arranged in a building so as to have an available fall of forty feet. The anvil is of an exceptionally rigid and heavy design consisting of two castings, each weighing 400 lbs., securely bolted to the top of four rolled steel joists, which in turn are bedded in concrete. The effective weight is 2,000 lbs. The test piece connects together the "tup" and arresting cross-head, and the whole is allowed to fall freely until the arresting piece strikes the anvil, when the specimen is broken and the tup continues to fall. The tup can be varied in weight 2 lbs. at a time between 10 lbs. and 20 lbs. Electric contacts are broken by the falling weight (1) at the moment of release, (2) on striking the anvil, and (3) after the tup has fallen 10 feet after fracture of specimen. By means of a Morse telegraph "inker," a pendulum half-second contact maker, and a vibrating tuning fork, the making and breaking of the electric contacts works the usual cronographic method, so that the times between the standard points given above can be ascertained to within about ·005.

[1] "Comparison of the Tensile, Impact-Tensile, and Repeated-Bendin Methods of Testing Steel." Proc. Inst. Mech. Eng., May 27th, 1910.

The time between points (1) and (2) merely serves as a check, while the time between (2) and (3) serves to calculate the energy remaining in the tup after fracture of the specimen.

The full expression for the energy of breaking is

$$\text{Energy absorbed} = W\left\{H - \frac{1}{2g}\left(\frac{h}{t} - \frac{gt}{2}\right)^2\right\}$$

where H is the height of free fall before striking anvil;
 h is the height of free fall after striking anvil, *i.e.*, between the anvil contact and the bottom contact;
 W is the weight of the tup; and
 t is the time-interval between the anvil and bottom contact.

It was found by the experimenters previously mentioned that the energy absorbed per cubic inch in an impact tensile test, divided by the elongation, gave a measure of the breaking stress in an ordinary tensile static test. The strength given by the impact test averaged about 1·2 times that given in a static test. It is worth noting that the authors of the above mentioned papers say, "The energy absorbed per cubic inch does not vary greatly with the various types of steel; it is approximately 50 per cent. more than that obtained by the static tensile test, and is also no definite criterion of the type of steel."

National Physical Laboratory Apparatus.[1]—The machine consists of a cast-iron anvil and a tup, each supported by four pieces of steel strip $\frac{1}{4}$ inch wide by $\frac{1}{30}$ inch thick and about 12 feet long. The anvil has two heavy bosses on the sides, through which passes two pieces of round steel bar. These can be adjusted to protrude any distance towards the middle of the anvil, and are locked by means of set-screws. The ends of these bars are cut away to hold the knife-edges, against which rests the specimen, kept at the right height by adjustable supports. The tup is provided with a steel knife-edge, adjustable outwards so as to just touch the specimen when the tup and the anvil are at rest.

[1] Described in Proc. Inst. Mech. Eng., 1905, p. 886.

From the back of both tup and anvil a string is carried over a pulley near the roof, with a small weight attached (just sufficient to keep the string taut). The rise of these weights is a measure of the height through which the tup or anvil is raised. The actual heights of the tup and anvil corresponding to the observed motions of the small weights on the strings is obtained by separate experiment.

The anvil weighs about 60 lbs. and the tup about 47 lbs. The specimens used in these tests were 5 inches long by $\frac{3}{8}$ inch square, and were notched on the tension side with a small V groove. The knife-edges were placed $4\frac{1}{2}$ inches apart. The method of test is as follows:—The specimen is placed in the anvil, and the tup tied back at the desired height by a piece of thin string. The tup is then released by severing the string with a sharp knife, and an observer notes the height to which the anvil is forced, while a second

TABLE V.—NICKEL ALLOYS FORGED AND COOLED FROM 800° C. (1,472° F.).

Ni. Alloy.	Shock Tests.			Hardness Tests.			
	Fall of 46·7 lbs. Hammer.	Energy Absorbed.	Bending Angle.	Indentation in $\frac{1}{1000}$ inch (Unwin's Test). Load 1·5 tons.	Indentation in $\frac{1}{1000}$ inch (Unwin's Test). Load 2·5 tons.	Brinell's Ball Test. Hardness Number.	Relative Hardness. Indentation Method. Swedish Iron = 1.
	Inches.	Inch lbs.	Degrees.				
A	13·23	451	18·0	7·2	15·0	202	1·6
B	13·05	428	17·0	6·4	14·5	207	1·8
C	13·67	454	16·5	7·0	19·5	212	1·6
D	13·92	460	15·5	6·0	12·3	217	1·5
E	13·67	217	Broken O.	4·2	8·7	321	—
F	13·67	105	Broken O.	2·5	5·5	532	—
G	14·15	230	Broken O.	2·5	5·7	578	2·2
H	14·17	436	7·5	3·2	6·2	555	2·2
J	13·33	432	14·5	5·0	10.3	293	2·0
K	13·77	452	28·0	16	40	131	1·2

observer notes the height to which the tup swings after the blow.

The work given as that required to deform or break the specimen is the difference between the kinetic energy of the system before and after the blow, calculated from the heights to which the masses are raised.

The preceding table from the Seventh Report of the Alloys Research Committee[1] shows some results obtained on the nickel alloys described in that paper.

For purpose of comparison hardness tests taken by means of (*a*) penetration of a hardened steel point, (*b*) Unwin's tests, (*c*) Brinell's ball test (see page 147), are given below.

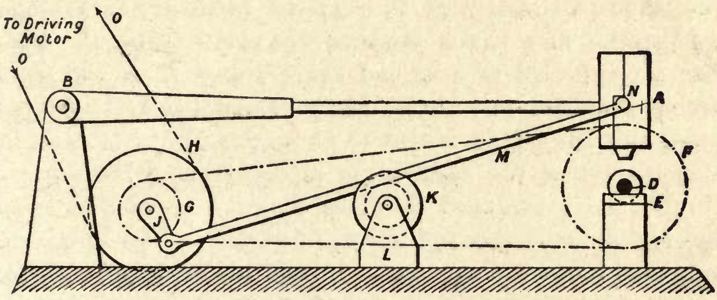


FIG. 95.—Impact Testing Machine, repeated Hammer Blows.

Seaton and Jude's Impact Testing Machine.—This is a simple machine and consists merely in arranging a weight attached to guides and arranged to fall through a definite distance on to a notched specimen held in a fixed anvil. A very usual size of specimen is 4 inches × ½ inch × ½ inch with a notch about ⅛ inch deep in the centre. This is held in the anvil so as to form a beam supported at the ends with about 3 inches span. The total falling weight is about 7 lbs., and is arranged to fall a distance of, say, 2 feet. After each blow the specimen is reversed and the blows continued until fracture occurs.

A Repeat Impact Testing Machine, which is a modified form of that originally designed by Dr. Stanton, is shown in

[1] Proc. Inst. Mech. Eng., 1905, p. 880.

diagrammatic outline in Fig. 95. A is a hammer head carried at the end of a lever, which is pivoted at B. The power is supplied by a belt OO, which drives a pulley H, which is in turn attached to a crank J. As this crank revolves it works a connecting rod M, whose motion is guided by a grooved pulley K. The end of the rod is thus caused to describe an irregular elliptical path, the amplitude of which varies with the position of the pulley K, which is adjustable. At N is a catch so arranged that as the end of the rod ascends it engages with this catch and raises the hammer to a height depending on the position of L. The connecting rod then moves forward and the hammer descends freely. The specimen, shown in section at D, is placed across the knife edges and gripped in a chuck attached to a chain pulley F. This later is connected to a second chain pulley G on the main driving shaft, the two wheels being geared 2 to 1. By these means the hammer is caused to strike the specimen twice in every revolution, the cycle being repeated about 100 times a minute. L is arranged to move along a graduated scale showing directly the fall of the hammer. The specimen under test is usually about ½ inch in diameter, with a groove turned at its centre to ensure its fracture there. The knife edges are cut slightly hollow, and a spring holds one end of the specimen in place. The chuck hold is so arranged that it does not take any portion of the hammer blow, all of which comes on the knife edges.

Although not shown in the diagram, there is an intervening mechanism between the chuck and the pulley F, by which the former does not have a uniform rotation, but a spring and trigger arrangement causes the specimen to have a step-by-step motion. That is to say, the specimen receives a blow, twists suddenly through 180 degrees, and remains stationary until another blow is struck, when, after the hammer has lifted, it again turns through 180 degrees. A revolution counter records the number of blows struck. When fracture occurs, the specimen falls away, the hammer head continuing to fall first works an electric switch which shuts down the

driving motor and then comes to rest on a steel stop pin. This machine is made by the Cambridge Scientific Instrument Company.

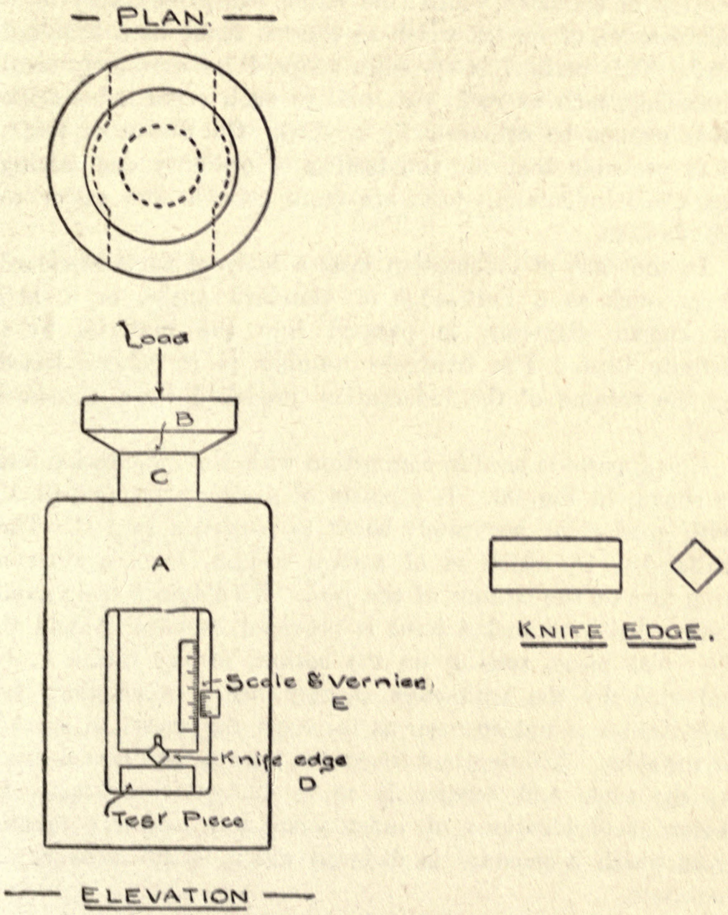


FIG. 96.—Unwin's Apparatus for Hardness Tests.

Hardness Tests.—Hardness tests may be divided into two chief classes, (*a*) scratch tests, (*b*) indentation tests. In the first of these methods a loaded diamond is pressed on the polished surface of the material, and the latter pulled so as to

cause the diamond to make a scratch. Standardisation may be taken either by basing the hardness factor or "number," as it is generally termed, on the load necessary to make a scratch of standard width (the latter being measured by a microscope), or on the width of scratch made by a standard load. This method is specially adapted for extremely hard materials, such as rock, etc., and in such cases indentation tests cannot be satisfactorily applied. On the other hand, it is probable that for the testing of ordinary engineering materials indentation tests are more reliable and easier to standardise.

In the case of indentation tests a body of some standard form, such as a knife-edge of standard angle, or a ball of known diameter, is pressed into the material by a definite load. The hardness number is in general based on the volume of the indentation produced by a standard load.

One apparatus used in connection with the indentation test is shown in Fig. 96. It consists of a strong framework A, with open sides, accurately bored to receive a ram C. The knife-edge D, which is of square section, rests against a true face on the bottom of the ram. To obtain a truly axial load a ball and socket joint is provided between B and C. The test piece, resting on the bottom of the frame A, is indented by the knife-edge D, care being taken that the indentation is not so deep as to cause the metal to spread at the sides. The depth of the groove thus formed is measured by the scale and vernier E as in the punching test. A series of observations of indentation and load are taken, from which a constant is deduced which is the measure of hardness.

The test piece is usually about $\frac{3}{8}$ inch square and $2\frac{1}{2}$ inches long, and the load is applied by placing the apparatus in an ordinary testing machine and applying a compressive load. It is necessary to standardise the machine by measuring the amount of compression which the machine itself undergoes apart from the indentation of the specimen. Prof. Uuwin has

shown that a relation between indentation and load takes place according to the formula—

$$Ci = p^{1 \cdot 2}$$

where i is the depth of the indentation in inches, p the pressure per inch of width of knife-edge producing the indentation, and C a constant for the material, termed the hardness number. Readings should be taken at varying loads, and the mean value of C calculated from the equation—

$$\log C = 1 \cdot 2 \log p - \log i.$$

The following are some values obtained by Unwin :—

Metal.	Value of C.
Cast steel, normal	554·0
Mild steel, normal	143·5
Copper, annealed	62·0
,, unannealed	105·2
Brass, No. 1	221·0
,, No. 2	246·0
Aluminium, squirted	41·8
,, alloy, cast	103·5
Lead, cast	4·2
Zinc, cast	40·8

Messrs. Calvert and Johnson used, instead of a knife-edge, a small truncated cone, and took as the measure of hardness, the weight which would indent the metal to a depth of $3\frac{1}{2}$ milimetres in half an hour. In some United States tests the volume of indentation produced by a pyramidal point loaded with a weight of 10,000 lbs. was used to measure the hardness of the material.

Brinell's Ball Test.—Since in all hardness tests in which the indenting tool has a sharp point or edge the latter is likely to become blunt, it is obvious that results may become dependent on the condition of the tool, and for this reason it is probable that a special ball offers the best form for making the indentation. This is the method employed by Brinell.

The test consists in pressing a hardened steel ball into the flat surface of the specimen under a known pressure and measuring the volume or curved area of the impression.

Fig. 97 shows one form of the apparatus employed.

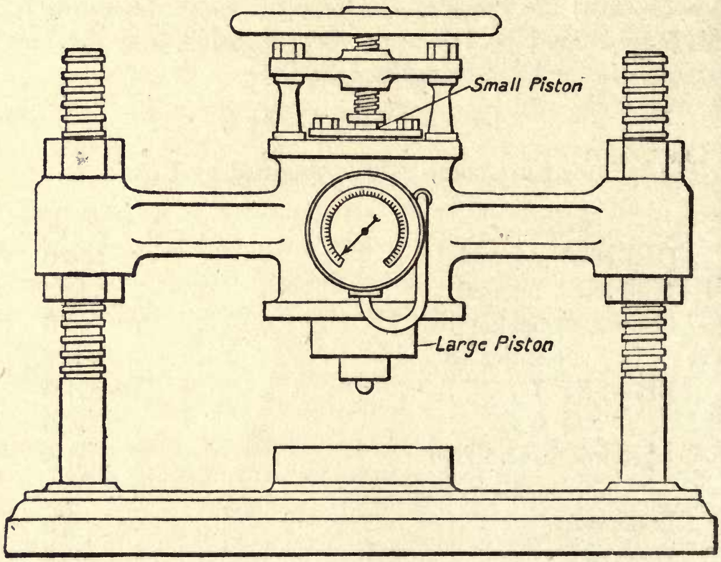


FIG. 97.—Brinell's Machine.

Brinell has taken as a basis of comparison

$$\text{Hardness number} = \frac{\text{Total pressure}}{\text{Curved area of impression}}.$$

$$\text{But curved area} = 2\pi r\left(r - \sqrt{r^2 - \frac{D^2}{4}}\right)$$

Where D is diameter of impression and r radius of ball.

$$\text{Whence H.N.} = \frac{P}{2\pi r\left(r - \sqrt{r^2 - \frac{D^2}{4}}\right)}$$

The number obtained by this formula will vary somewhat for different value of P and r, hence Brinell has fixed the standard by taking $r=5$ millimetres, and $P=3{,}000$ kilogrammes, D being in millimetres.

It has been shown by Benedicks of Upsala that for balls of different radius a constant value is obtained by multiplying the above hardness number by $\sqrt[5]{r}$. Or Benedick's hardness number=(Brinell's H.N.)$\sqrt[5]{r}$.

Various types of machines for applying the Brinell test have been devised, notably by Guillery and by Brinell himself.

The following table, given by Prof. Warren, of the University of Sydney, gives a ready means of determining the hardness number from the diameter of the depression :—

TABLE VI.—RELATION BETWEEN THE DIAMETER OF THE IMPRESSION AND BRINELL'S HARDNESS NUMBER.

Diameter of Impression. Mm.	Hardness Number for the Pressure in kgs.		Diameter of Impression. Mm.	Hardness Number for the Pressure in kgs.	
	3,000	500		3,000	500
2·00	946	158	2·75	495	83
2·05	898	150	2·80	477	80
2·10	857	143	2·85	460	77
2·15	817	136	2·90	444	74
2·20	782	130	2·95	430	73
2·25	744	124			
2·30	713	119	3·00	418	70
2·35	683	114	3·05	402	67
2·40	652	109	3·10	387	65
2·45	627	105	3·15	375	63
2·50	600	100	3·20	364	61
2·55	578	96	3·25	351	59
2·60	555	93	3·30	340	57
2·65	532	89	3·35	332	55
2·70	512	86	3·40	321	54

TABLE VI.—*Continued.*

Diameter of Impression. Mm.	Hardness Number for the Pressure in kgs.		Diameter of Impression. Mm.	Hardness Number for the Pressure in kgs.	
	3,000	500		3,000	500
3·45	311	52	5·20	131	21·8
3·50	302	50	5·25	128	21·5
3·55	293	49	5·30	126	21·0
3·60	286	48	5·35	124	20·6
3·65	277	46	5·40	121	20·1
3·70	269	45	5·45	118	19·7
3·75	262	44	5·50	116	19·3
3·80	255	43	5.55	114	19·0
3·85	248	41	5·60	112	18·6
3·90	241	40	5·65	109	18·2
3·95	235	39	5·70	107	17·8
			5·75	105	17·5
4·00	228	38	5·80	103	17·2
4·05	223	37	5·85	101	16·9
4·10	217	36	5·90	99	16·6
4·15	212	35	5·95	97	16·2
4·20	207	34·5			
4·25	202	33·6	6·00	95	15·9
4·30	196	32·6	6·05	94	15·6
4·35	192	32·0	6·10	92	15·3
4·40	187	31·2	6·15	90	15·1
4·45	183	30·4	6·20	89	14·8
4·50	179	29·7	6·25	87	14·5
4·55	174	29·1	6·30	86	14·3
4·60	170	28·4	6·35	84	14·0
4·65	166	27·8	6·40	82	13·8
4·70	163	27·2	6·45	81	13·5
4·75	159	26·5	6·50	80	13·3
4·80	156	25·9	6·55	79	13·1
4·85	153	25·4	6·60	77	12·8
4·90	149	24·9	6·65	76	12·6
4·95	146	24·4	6·70	74	12·4
			6·75	73	12·2
5·00	143	23·8	6·80	71·5	11·9
5·05	140	23·3	6·85	70	11·7
5·10	137	22·8	6·90	69	11·5
5·15	134	22·3	6·95	68	11·3

Professor Warren gives some interesting figures showing the relation between the tensile strength and the hardness as obtained by Brinell's ball test.

TABLE VII.

Tensile Strength. Tons per sq. in.	Brinell's Hardness Number.	Ratio of the Tensile Strength to Hardness Number.
28·9	170	·170
30·2	149	·203
25·3	141	·180
25·6	140	·183
27·0	140	·193
25·8	140	·184
24·9	137	·182
25·6	134	·191
Mean 26·7	143·9	·186

The above figures were obtained on structural steel, the ball being 10 millimetres diameter; pressure 3,000 kilogrammes.

It will be observed that the value obtained by dividing the actual tensile strength by the Brinell's hardness number is fairly constant for the same quality of steel.

In the case of axle steel the following was obtained—

TABLE VIII.

Tensile Strength. Tons per sq. in.	Brinell's Hardness Number.	Ratio of the Tensile Strength to Hardness Number.
34·0	167	·202
36·5	168	·216
33·95	205	·165
Mean 34·8	180	·194

Dillner, of Stockholm, has investigated this same relation between tensile strength and hardness number, and found with only a mean error of 3·3 per cent. that the tensile strength in tons per sq. in. for steels having a hardness number below 175 could be obtained by multiplying the

hardness number by 0·230 when the indentation was made transversely to the direction of rolling, or 0·225 when made in the direction of rolling.

The "Scratch" Test is used by Prof. Turner in his "scleormeter." This consists of a perfectly balanced lever, which has a diamond point at one end. The whole arrangement can be moved from side to side, so as to make a scratch on the smooth surface of the metal to be tested. The load on the point can be varied by adding weights to a small scale pan on the lever, and the weight in grams acting on the diamond point required to produce a standard scratch is used as a measure of the hardness of the metal.

In connection with hardness tests an important communication upon the subject was compiled by Prof. Thomas Turner,[1] M.Sc., from which the following observations are obtained. He compared four methods, viz.: (1) Turner's sclerometer; (2) Shore's scleroscope; (3) Brinell's test; (4) Keep's test. It may be mentioned that method (2) involves the use of a new patent, viz., the scleroscope. In this instrument there is a small cylinder of steel with a hardened point. This is allowed to fall on the smooth surface of the metal to be tested, and the hardness of the material is taken by measuring the rebound. Prof. Turner says: "Each form of test has its advantages and its limitations. The sclerometer is cheap, portable, and easily applied, but it is not applicable to materials which do not possess a fairly smooth reflecting surface, and the standard scratch is only definitely recognised after some experience. The Shore test is simple, rapid, and definite for materials for which it is suited, and appears likely to have an important future. But further information is yet needed as to the exact property which is measured by this form of test. As shown by De Fréminville, the result obtained varies somewhat with the size and thickness of the sample, while if the test piece is supported on a soft material such as a plasticine the results are valueless. It may, however, be pointed out that indiarubber gives a

[1] *Journal of the Iron and Steel Institute*, 1909.

rebound of 23, which is equal to that of mild steel; while I have found light soft pine-wood give a rebound of 40, which is nearly double as great as that of grey cast-iron. Curiously enough hard wood, like teak, gives a rebound of about 12, while some samples are considerably lower than this. As illustrating the influence of the support, a sample of exceptionally hard rolled copper about $\frac{1}{25}$ of an inch in thickness, when supported on a block of hard steel and tested with the blunt or "magnified" hammer supplied, gave a value of 30, which was increased to 34 when the copper was supported on wood. A sample of brass only gave a value of 17, and yet this brass would scratch the copper, while the copper would not scratch the brass. From these results it is evident that the Shore test is only applicable to a certain class of substances. It appears to test what may be termed the "elastic hardness," and gives high results with metals in the "worked hard" or *écroui* condition; values which are not fully confirmed by the tool or by the sclerometer. My tests appear to show that good results are, however, obtained with glass and with porcelain, as well, of course, as with most metals. The Brinell test is specially useful for constructive material; it is easily applied and definite, and is now of all hardness tests the one most employed. It appears to give satisfactory results with wood, but cannot be applied to very brittle materials such as glass, or to hard minerals. Keep's test is specially suited for castings of all kinds, as it records not merely the surface hardness, but also that of the whole thickness, and gives indications of blowholes, hard streaks, and spongy places. Obviously it can only be applied to materials the hardness of which is less than that of hardened steel."

Curiously enough, however, it may be noted that all four methods give comparative results for all pure metals in their normal condition. The following results, obtained from the experiments of Prof. Turner, will give an idea of the closeness of agreement and the actual values of various materials.

Other tests of hardness are grinding, machining and

drilling tests, but the methods most used are those described above.

TABLE IX.—HARDNESS SCALES COMPARED.

Metal.	Turner. (Sclerometer.)	Scleroscope.	Brinell. 6.	Keep.
Lead . . .	1·0	1·0	1·0	
Tin . . .	2·5	3·0	2·5	
Zinc . . .	6·0	7·0	7·5	
Copper, soft .	8·0	8·0	—	Angle varies from 0° to 90°.
,, hard .	—	12·0	12·0	
Softest iron . .	15·0	—	14·5	
Mild steel . .	21·0	22·0	16-24	
Soft cast-iron .	21-24	24·0	24·0	
Rail steel . .	24·0	27·0	26-35	
Hard cast-iron .	36·0	40·0	35·0	
Hard white iron .	72·0	70·0	75·0	
Hardened steel .	—	95·0	93·0	

Combined Static and Shock Tests.—At a meeting of the Physical Society (October, 1910) Mr. Rogers presented a paper describing the results of tests made upon steel specimens subjected to stresses caused (simultaneously) by bending and shock, or impact. It appears that the results would be easier to interpret if the static load were either tension or compression. The work of Mr. Rogers is important, as the author believes it was the first published on combined static and impact tests. It should suggest the lines of further interesting experiments.

CHAPTER VIII

SHEAR AND MISCELLANEOUS TESTS

DIRECT shear or "rivet" tests, that is to say shear tests as distinct from torsion tests, are not very frequently carried out, owing to the difficulty of ensuring pure shear without bending. When such experiments are made they are generally performed in an ordinary "omnibus" machine arranged for tension or compression, use being made of a special form of shackle. There are many forms of the latter, and such will readily suggest themselves to the student as modifications of the single example taken.

Shearing Shackles.—This apparatus, shown in Fig. 98, consists of two rectangular blocks A and B, which are bolted together by the four bolts C, D, E, F. Down the centre of these blocks is cut a rectangular channel G, in which a rectangular piece H is allowed to slide. The three discs K, L, and M fit accurately in a hole which is bored through A and B, and are fixed in position by the hollow nuts N and O. The specimen is supplied in the form of a cylindrical bar, which accurately fits inside the holes in K, L and M. When the bar is in position the load is applied to H, and the specimen is sheared off at the joints between K and L and L and M, the strength in double shear thus being ascertained. It is important that the faces of K, L and M should be perfectly true, as if there is any space between them the material is not in pure shear, but partly in bending.

Shear Tests.—With this apparatus tests on materials can be carried out in either single or double shear. The bearing surface should always be kept as large as possible, so that when making tests in single shear, the specimen should be

pushed so far through the middle die that it just misses fouling the end die.

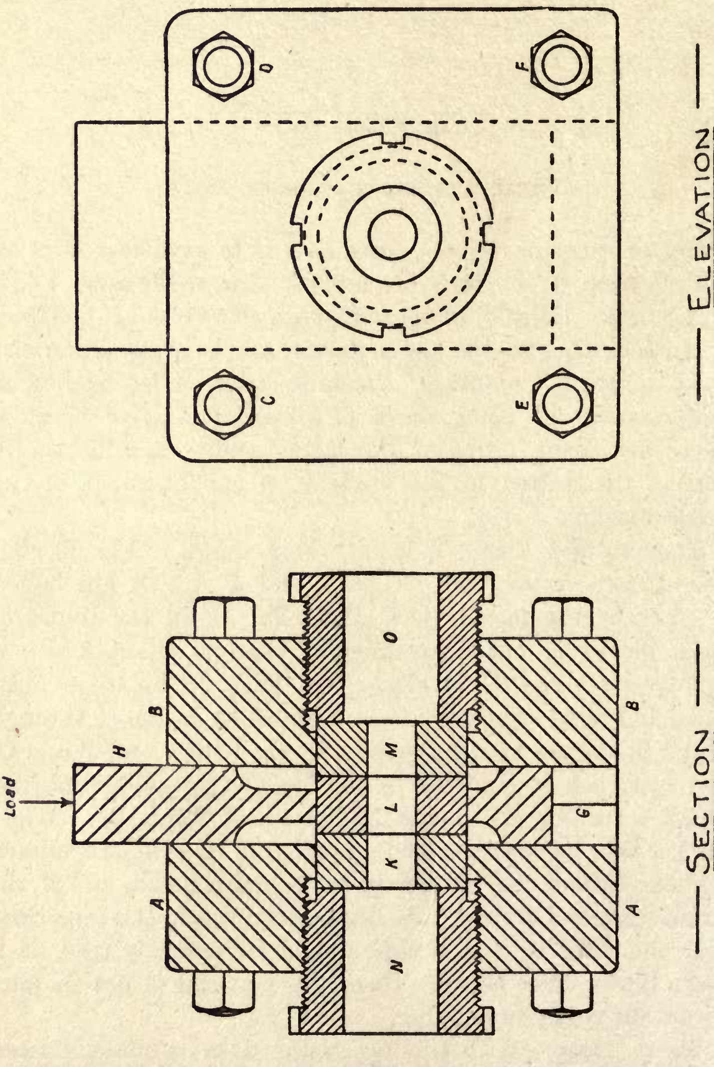


FIG. 98.—Apparatus for Shearing Tests.

To avoid errors due to bending the specimen should be a very good fit in the dies, and for the same reason there should be no clearance between the latter when in position.

The following results were obtained for mild steel, wrought-iron, and cast-iron in both double and single shear :—

TABLE X.

Material.	Method of Shear.	Diameter. Inches.	Area. Sq. in.	Load. Tons.	Shear Stress, Tons, per sq. in.
Mild steel .	Double	·875	·601	21·66	18·02
" " .	Single	·875	·601	10·90	18·14
Wrought-iron	Double	·877	·606	20·97	17·32
" "	Single	·877	·606	10·38	17·20
Cast-iron .	Double	·871	·596	15·12	12·70
" " .	Single	·874	·600	7·48	12·47

As will be seen from the table, the strength of a material in double shear is about twice that in single shear.

In addition to thus testing in single and double shear some interesting and useful results can be obtained by testing in shear specimens cut from the same bar as those specimens tested in tension. From such results valuable information can be gained as to what proportion of the tensile stress is to be taken for a corresponding safety factor in shear.

The following table gives actual results :—

TABLE XI.

Material.	Breaking Tension.	Shear Stress.	Ratio.
	Tons per	sq. in.	
Best Staffordshire iron . .	24·41	19·35	·793
Yorkshire iron . . .	23·13	18·02	·781
Mild steel bar . . .	28·64	20·04	·700
Steel boiler plate . . .	27·17	18·68	·688
Spring steel	48·10	30·84	·642
Copper plate	14·33	9·96	·695

It is probable that, with such tests, a pure shear is never obtained because of the complication due to bending. The most satisfactory method of obtaining pure shear is that of

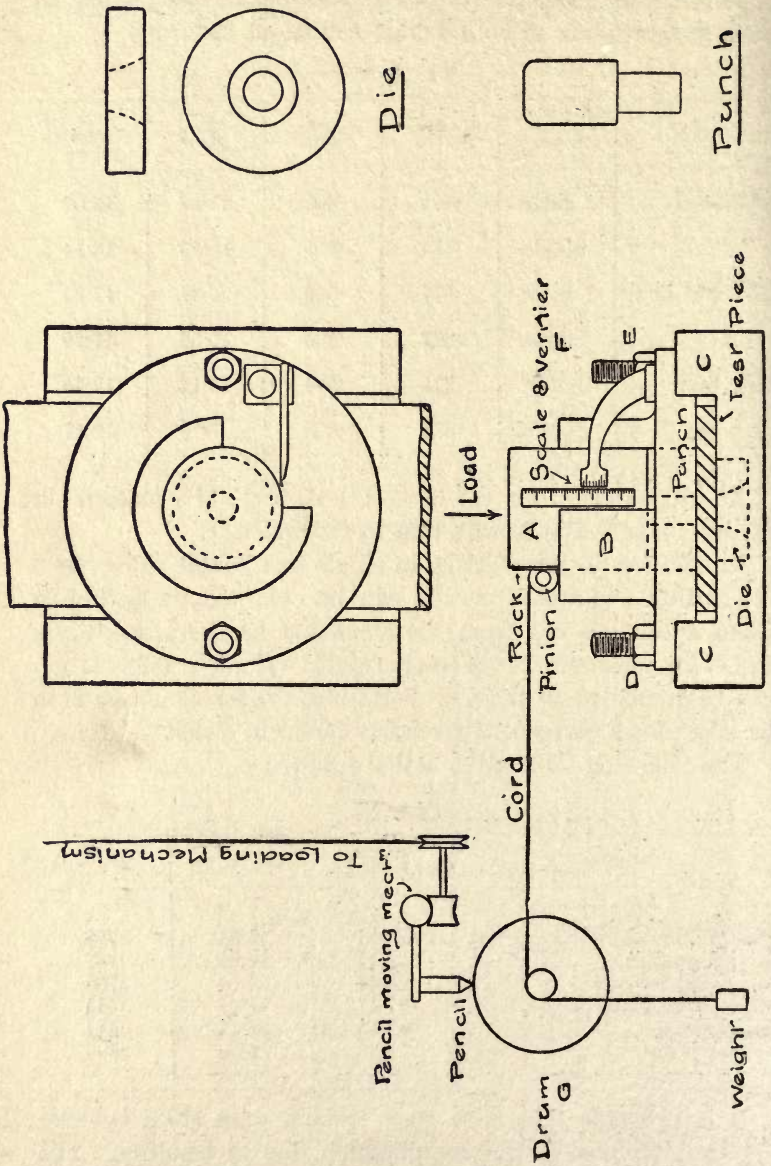


FIG. 99.—Apparatus for Punching Tests.

using a hollow specimen for a torsion test. At the same time the results obtained of this "rivet shear" test are valuable, as they are obtained under conditions such as take place in practice.

Punching Tester (Fig. 99). — The apparatus consists essentially of a steel cylinder A which slides up and down in a cylindrical guide B. The test piece, consisting of a plate of the required material, is secured tightly between the bottom

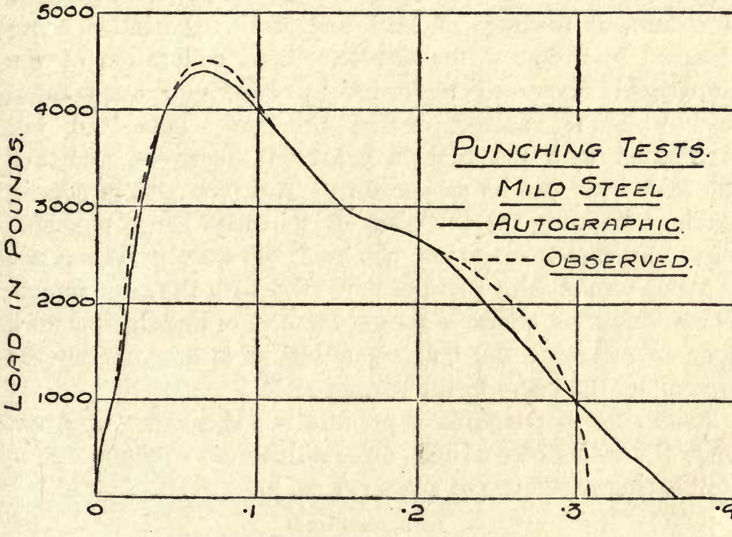


FIG. 100.—Punching Test on Mild Steel.

of B and the base plate C by means of the bolts D, E. The punch is fastened to the cylinder A, while the die fits in a corresponding recess in the base plate C. The load is applied vertically downwards on the cylinder A, and the punch thus driven through the test plate. The strain of the metal can be read for any given load by means of a scale fitted to A, and a vernier attached to the guide B. The tests can also be automatically recorded by the following arrangement. The downward movement of A, and consequently the yielding of the specimen, is transmitted by means of a rack and pinion, through a stretched cord to a drum G, which thus rotates in

proportion to the strain of the test plate. The pencil is moved along the axis of the drum by means of a cord or wire from the loading mechanism, its movement being proportional to the load on A. Hence the diagram recorded is a stress-strain curve, and the work done in punching out the plate can be obtained from it in the usual way.

Punching Tests.—By means of this apparatus, load-strain diagrams can be obtained either autographically or by plotting simultaneous readings of load and strain, the latter being obtained by means of the vernier. Load calibration of the autographic diagram is performed by observing the maximum load which is reached during the test. This load will correspond with the highest point on the curve, and thus the load scale can be determined. The strain is, of course, obtained knowing the thickness of the plate being punched. Fig. 100 shows diagrams obtained by each of these two methods on the same plate of mild steel with the same punch. These diagrams afford a simple method of finding the work done in punching the hole, equalling, as it does, merely the area under the curve to the correct scale.

Resistance to punching is practically a shearing resistance. Then if d=diameter of hole, and t=thickness of plate—

Shearing resistance of plate per sq. in.

$$=\frac{\text{maximum load}}{\pi dt}.$$

For comparison these quantities have been calculated for the two curves, Fig. 100.

Mild Steel Specimen.

$$\begin{cases}\text{Diameter of punch} = \cdot 870 \text{ inches.}\\ \text{Thickness of plate} = \cdot 359 \quad ,,\end{cases}$$

From autographic diagram.

Maximum load = 43,800 lbs. per sq. in.

Work done in punching hole = 700 ft. lbs.

$$\text{Maximum punching resistance of plate} = \frac{P}{\pi dt} = \frac{43{,}800}{\pi \times \cdot 870 \times \cdot 359}$$

$$= 44{,}750 \text{ lbs. per sq. in.}$$

Diagram from observed readings.

Work done in punching=725 ft. lbs.

$$\text{Maximum punching resistance} = \frac{45{,}200}{\pi \times \cdot 87 \times \cdot 359}$$
$$= 46{,}100 \text{ lbs. per sq. in.}$$

Tests of Steel Balls.—The testing of steel balls in a satisfactory manner presents some difficulty, as it is not an easy matter to obtain a surface which will not become indented

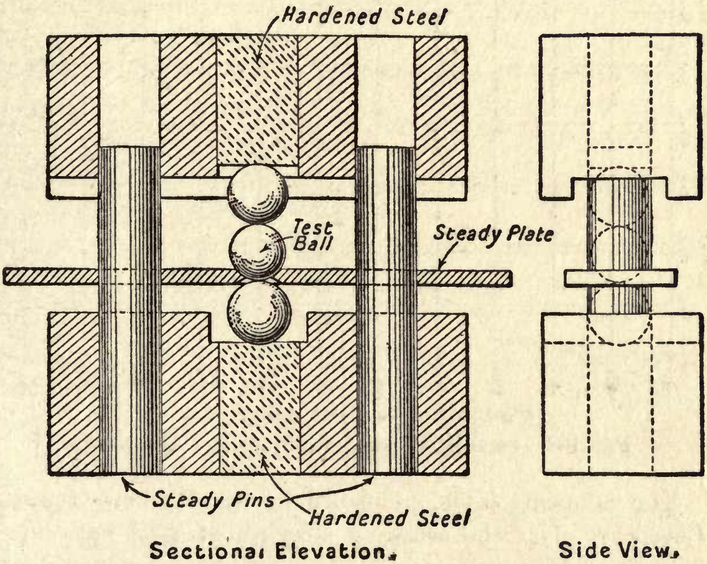


FIG. 101.—Apparatus used for Testing Steel Balls.

before the pressure becomes sufficiently great to crush the ball.

Up to sizes of about $\frac{3}{8}$ inch diameter hardened steel plates, between which to crush the ball, can be used with moderate success, but with balls of larger diameter than this, the plates either indent, or if sufficiently hard, actually crack.

A method of testing the larger sizes of balls at the East London College, which has been found to answer very successfully, is roughly as follows. The ball to be tested is supported between two other balls, these in turn exactly fitting

into turned recesses in hardened steel blocks. With such an arrangement the centre ball, *i.e.*, the one to be tested, breaks first, almost without exception, and in addition a point contact is obtained. Fig. 101 shows the apparatus employed.

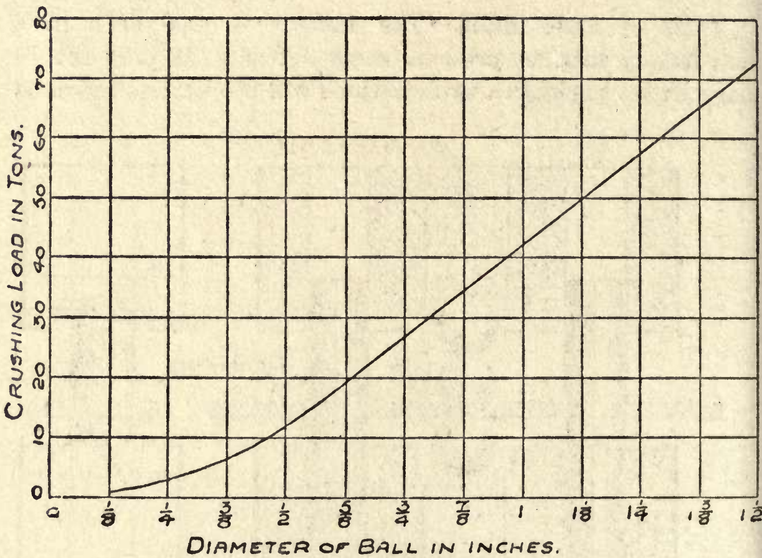


FIG. 102.—Steel Ball Tests. Published by "Machine Co."

The following table, published by the Machine Company, Coventry, gives the crushing strength of steel balls up to $1\frac{1}{2}$ inch in diameter :—

TABLE XII.

Size of Ball.	Crushing Load.	Size of Ball.	Crushing Load.	Size of Ball.	Crushing Load.
Inch.	Tons.	Inch.	Tons.	Inch.	Tons.
$\frac{1}{8}$	·574	$\frac{7}{16}$	8·70	$1\frac{1}{8}$	43·75
$\frac{5}{32}$	·893	$\frac{1}{2}$	11·82	$1\frac{3}{16}$	49·05
$\frac{3}{16}$	1·297	$\frac{9}{16}$	15·61	$1\frac{1}{4}$	58·00
$\frac{7}{32}$	2·009	$\frac{5}{8}$	21·65	$1\frac{3}{8}$	64·70
$\frac{1}{4}$	2·99	$\frac{3}{4}$	29·90	$1\frac{1}{2}$	73·60
$\frac{5}{16}$	4·01	$\frac{7}{8}$	34·80		
$\frac{3}{8}$	6·39	1	41·25		

These results are shown graphically in Fig. 102.

If a curve be plotted between the squares of the diameters of the balls and the crushing load, an approximately straight line is obtained, showing that a proportionality exists between these two quantities.

The most usual form of failure is a vertical fracture extending the whole length of the ball.

Sometimes, however, the ball breaks into several pieces, or it may be partly crushed to powder.

Roller Test.—When a cast-iron specimen is tested as a roller, fracture occurs in a longitudinal vertical plane through the axis of the specimen, loose wedge-shaped pieces falling out along the two lines of contact. The stress, of course, is variable over the section, but in the test given below the compressive stress has been calculated as distributed uniformly over the projected area of the roller.

TABLE XIII.

COMPRESSION TEST—CAST-IRON.

No. of Specimen.	Diameter.	Area.	Length.	Crushing Load.	Crushing Stress.
				Tons.	Per sq. in.
1 .	·730″	·418	2·40	24·43	58·4
		Tested as	Roller.		
4 .	·726″	1·833	2·525	24·66	15·59

Rough Shop Tests.—In most specifications for materials it is usual to specify certain comparatively rough tests besides the more refined methods of machine testing such as have been previously described. Thus in the case of cast-iron it is usual to insert a clause to the effect that, at every pouring, one or two bars shall be cast having dimensions in the neighbourhood of 3 to 4 feet long, and having a section from 2 inches by 1 inch to 1 inch square; and that when such bars are placed on supports, say 3 feet apart, they shall support a central load of a specified amount. The Admiralty specification for cast-iron is a breaking load of 2,000 lbs. on a beam 1 inch square with

supports 1 foot apart. Such tests are frequently performed in a foundry merely by placing the bar on the edges of two moulding boxes placed the specified distance apart, and hanging foundry weights to the centre until fracture occurs. The weights are then placed on a weighing machine, and it is at once seen whether the bar comes within the specification. When, however, as is sometimes done, deflections are specified, and in foundries where a large amount of Government and similar work is carried out, proper machines are used. Fig. 103 indicates in outline the general principle of one very good type of machine for this purpose. It will be seen that the load is

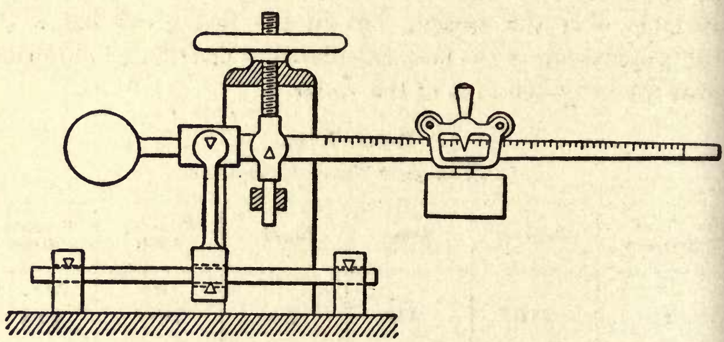


FIG. 103.—Small Beam Testing Machine for Cast Iron.

applied by a hand-wheel and screw, and this load is balanced and measured by moving a weight along a graduated beam. In the case of the more powerful machines the load is applied through compound gearing. The moving weight is made so that it can be varied by placing disc weights on to it, and thus making the machine capable of accurate measurement over a wide range of beam sizes.

Rough mechanical tests for ductile materials are those known as cross-bending, folding or doubling tests. Thus the Admiralty specify that specimens of steel forgings 1 inch square shall be capable of being bent cold through an angle of 180° over a radius not greater than ¼ inch. Specimens of copper pipes must stand bending through 180° cold until the

two sides meet, and of hammering to a fine edge without cracking. The method of carrying out such tests is obvious, but it must be borne in mind that to a certain degree such tests depend to a more or less extent upon the skill of the smith who performs them, and it is necessary that they should always be performed by a skilful and unbiassed hand, as otherwise, except in the case of materials which easily fulfil the test, it is comparatively easy to cause the material to fail.

Tests on Wires.—Many instructive experiments, especially by way of preliminary to large size specimens, can be carried out on wires. A wire of iron or steel is stretched about 0·001 inch per ton per sq. inch stress, and as elastic extension can be taken up to, say 10 tons per sq. inch, this is equivalent to a maximum extension of 0·01 inch per foot. If a wire from 20 to 100 feet long is employed, deflections are obtained of from 0·2 inch to 1 inch, and such can be easily and with fair accuracy read by means of an ordinary scale and vernier. In all tension tests on long wires it is desirable, in order to eliminate temperature effects and the deflection of the supports, to suspend two wires of the same material side by side, one of which is held taut by a fixed load and carries the scale, while the loaded wire carries the vernier. When very long wires are employed it is necessary to carry the wires over pulleys, and in order to eliminate the friction of the latter it is necessary to take two sets of readings with increasing and decreasing load. The mean of these two gives the true deflection without friction. When short wires are tested in tension it is necessary to employ some magnifying arrangement for the extension. This can be performed by arranging a small mirror so arranged as to be tilted by the extension of the wire. The deflection of the mirror is seen either by arranging a source of light so that the motion of the mirror moves a beam of light across a scale, as seen in the sphingometer (see page 68), or else a telescope is moved, as in the Bauschinger extensometer (see page 61). Remembering that the angle turned through by the beam of light is twice the

angle moved by the mirror, it is generally a simple matter to calculate the extension of the wire from the direct readings.

Prof. Burr has devised an ingenious method of taking autographic diagrams with wires. A long wire is suspended, and carries at its lower end a fair sized bucket. A pencil gear is attached to the wire so that as it extends it draws a line down a sheet of paper attached to a drum. Close to the bucket at the end of the wire is a second bucket filled with sand and provided with an outlet so that this sand can run out into the first bucket. The bucket of sand is suspended by a spring and a cord in such a manner that, as the sand runs out, the bucket becomes lighter, allowing the spring to contract, and turning the drum round on its axis by means of a second cord, also attached to the spring. It is obvious, therefore, that the angular motion of the recording drum will be proportional to the load, while the movement of the pencil gear will be proportional to the extension. The result is a stress-strain curve drawn on the sheet attached to the drum.

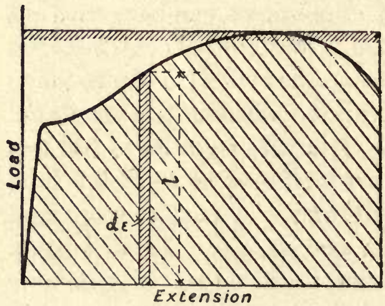


FIG. 104.—Work done in Breaking Specimen.

Work done in Fracturing a Specimen.—It is clear from the fact that since work done is equal to force into distance, and that the ordinary so-called stress-strain curve shows the relation between load and distance moved by the same, then

Work done in fracturing specimen $= \int lde$, which is clearly the area shown in Fig. 104 by the cross-hatched lines. This should be measured by the student, and the work done in fracturing the bar calculated per pound and cubic inch of material. Prof. Marten has recently stated

a rather important point in connection with the area thus obtained.[1]

If we draw round the curve of load and extension a circumscribing rectangle, then he calls the ratio of the area of the load-extension diagram to the area of the circumscribing rectangle ξ. The important and somewhat curious point is that ξ is practically a constant for all conditions of the *same* material, whether such conditions are produced by hammering, annealing, or any other treatment. Thus in Fig. 105 two curves are shown. One for wrought-iron after long-continued cold hammering and working, and another for the same material after annealing. Then

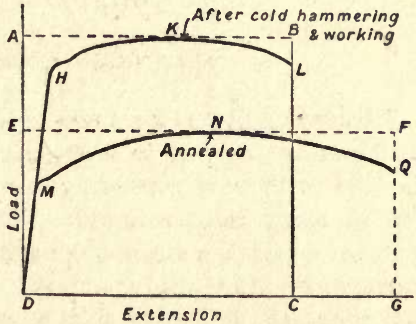


FIG. 105.—Load-Extension Curves showing Effect of Annealing on Mild Steel.

$$\frac{\text{Area DHKLC}}{\text{Area ABCD}}=\frac{\text{Area DMNQG}}{\text{Area DEFG}}=\xi.$$

This probably only applies to mild steel and wrought-iron, but it would be worth the student's while to see if he can get any relation which remains fairly constant for different changes of state.

[1] *Zustandsänderungen der Metalle infolge von Festigkeitsbeanspruchungen.* A. Marten, Preuss. Akad. Wiss. Berlin, Sitz. Ber. 11, pp. 209—220, 1910.

CHAPTER IX

ALTERNATING STRESS TESTS

Alternating Stress Machines.—Many structures or parts of machines are subject to alternating stresses, that is to say the load on them is constantly being increased or decreased, and in many cases reversed. The diagonal bracing in the centre of a bridge, a steam-engine connecting rod, or a railway-carriage axle are typical examples. It is important, therefore, that materials subject to such stresses should be tested under similar conditions, and the following machines have been devised to that end :—

The pioneer of this type of test was Wöhler, who, in 1871, published valuable researches with reference to the effect of alternating stress upon the strength of materials. Other prominent workers in the same field have been Prof. J. O. Arnold, Captain Sankey, and Dr. Stanton, all of whom have invented machines capable of performing alternating stress tests. Such tests are useful for experimental investigations, and are of advantage in some commercial cases. The static test will probably always remain the chief method used in commercial work. It is, however, desirable that the value of alternating stress experiments, especially when applied to new steel and other alloys, should not be underrated.

Wöhler's Machine for Testing Alternating Torsional Stresses.—This is illustrated in Fig. 106. The test bar A is a simple cylindrical bar with enlarged ends, held in suitable chucks and supported by two bearings B, C.

To the end of the mandril passing through the bearing C is attached a lever D, which carries knife-edges at its end. H is a vertical rod attached at its lower end to a horizontal lever P, and having at E and F adjustable collars which bear on the

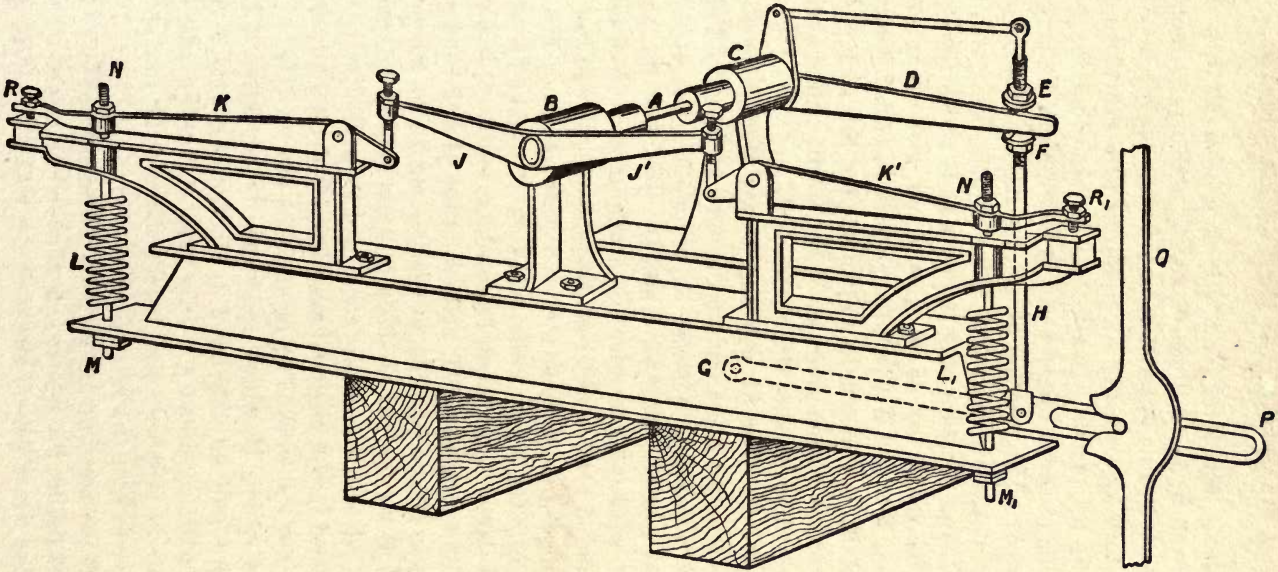


FIG. 106.—Wöhler's Alternating Torsion Testing Machine.

knife-edges. The lever P, which is pivoted at G, is moved up and down by the connecting rod Q, and arrangements are made by which this latter lever can be put rapidly in and out of gear; also by means of a slotted link in P the stroke of the latter can be varied. It will thus be seen that the vertical oscillations of Q are transformed to twisting oscillations of the specimen A. The reaction of the torque thus transmitted is taken by means of the system of levers J J_1, K K_1, etc., to the springs L L_1. By adjusting the nuts at E and F the stroke of D can be varied so as to give equal stresses in opposite directions. N N_1 and M M_1 are then adjusted, so that the contacts at R and R_1 are alternately lifted against the spring by the reaction of the torque given to the specimen. Different stresses are obtained by varying the stroke of P.

Wöhler's Tension Alternating Stress Machine.—Fig. 107 shows in diagrammatic outline the machine used by Wöhler in his tension alternating stress experiments. The specimen A is held in suitable shackles B and C. The low shackle C is made of adjustable height by means of a screwed tail rod, which can be fixed in different positions relative to the frame of the machine by means of the nuts shown. The upper shackle B is carried on knife-edges on the end of a beam C, which is supported, also on knife-edges, at D. Q is a vertical oscillating connecting rod, and by means of a slot and pin can be made to give a variable oscillating stroke to the lever E. The end of the lever C carries a link attached to the horizontal beam J, whose other end is connected to a similar lever and spring used in the torsional machine. The oscillations of the lever E are transmitted by means of a pin working in a slot F to the spring H, which consequently transmits a varying downward pull on the lever J, and hence causes a variable stress on the specimen A. It is obvious that the pull on the specimen is proportionate to the tension of the spring L necessary to keep the lever K from rising.

To set the machine for giving a stress alternating between two fixed limits, the spring L is adjusted by means of the nut M, so that the *minimum* stress would make the lever K rise.

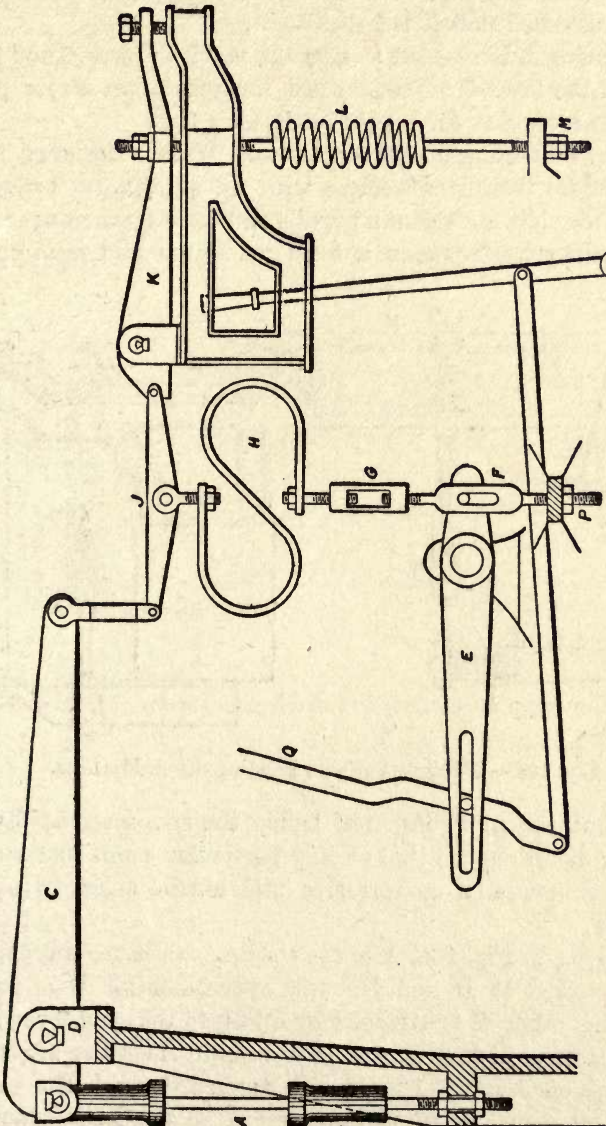


FIG. 107.—Mechanism of Wöhler's Tension Alternating Stress Machine.

The nut P and the right- and left-handed coupling nut G are then adjusted so that K is just lifted.

The spring L is now set to give the *maximum* stress, and the stroke of the lever E adjusted until the maximum stress just raises the lever K. All is now ready for a test.

Wöhler's Bending Stress Machines.—Wöhler designed two machines for testing specimens with an alternating bending stress. One shown diagrammatically in Fig. 108 is arranged for varying the stress between a fixed maximum and minimum,

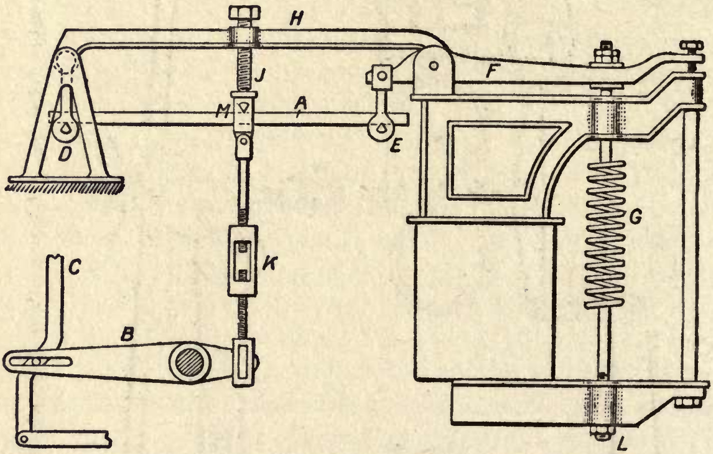


FIG. 108.—Wöhler's Variable Bending Stress Machine.

while that shown in Fig. 109 bends the specimen rapidly in opposite directions, so that at any particular point the stress alternates between a compressive and tensile stress of equal intensity.

Referring to Fig. 108, A is the specimen (a beam) supported on knife-edges at D and E. One of these latter D is fixed, while the other E is attached by a link to the same lever and spring arrangement which we have seen in the other alternating stress machines. The load is applied through the usual oscillating connecting rod and lever B to the knife-edge M. The lever B is attached to the vertical rod K by a pin working in a seat, so that no upward push can be given to the beam.

To set the machine for a required variation, the spring G is adjusted by the nut L to such a load that the beam F is lifted by the minimum load to be applied to the beam. The screw J, which is rigidly held by the fixed cross-beam H, is then screwed down until F justs lifts. G is now tightened up by the nut L to the maximum load, and the stroke of the lever B adjusted until the lever F is just lifted at the end of the stroke. All is now ready for a test. Adjustments in the length of K can be made by means of a turn-buckle, while the stroke of B

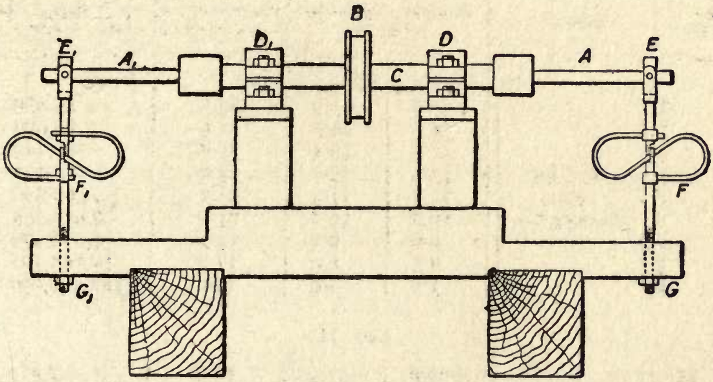


FIG. 109.—Wöhler's Machine for Repeat Bending in opposite directions.

is varied by moving the attachment pin on C along a slotted link.

In the second bending stress machine shown in Fig. 109 two specimens are used, A and A_1; these are fixed by driving into two chucks placed at either end of a mandril C, running in bearings D and D_1, and carrying a pulley B. The specimens are first turned in a lathe, so that they shall be perfectly straight, and then bearings are attached to them at F and E_1 of such a kind that a downward pull can be exerted at these points by means of two spring balances F and F_1. The pull of these, which were of a special kind, shown diagrammatically in the figure, could be varied by adjusting the nuts at G and G_1. It is obvious that when the pulley B is rotated the specimens will be subjected to a bending which is equivalent to being

rapidly bent backwards and forwards in opposite directions. The load, in fact, is similar to that acting on the axles of a railway coach when running.

TABLE XIV.—WÖHLER'S EXPERIMENTS ON BARS SUBJECTED TO REPETITIONS OF TRANSVERSE STRESS (ROTATING BARS) BETWEEN EQUAL AND OPPOSITE LIMITS OF STRESS.

SET I.

No. of Bar.	Material.	Stress applied in tons per sq. in.		Range of Stress in tons per sq. in.	No. of Repetitions before Fracture.
		Maximum.	Minimum.		
1	Iron for axles, Phœnix Co.	+15·3	−15·3	30·6	56,430
2		14·3	14·3	28·6	99,000
3		13·4	13·4	26·8	183,145
4		12·4	12·4	24·8	479,490
5		11·5	11·5	23·0	909,840
6		10·5	10·5	21·0	3,632,588
7		9·6	9·6	19·2	4,917,992
8		8·6	8·6	17·2	19,186,791
9		7·6	7·6	15·2	132,250,000[1]

SET II.

No. of Bar.	Material.	Maximum.	Minimum.	Range of Stress in tons per sq. in.	No. of Repetitions before Fracture.
24	Homogeneous iron.	+23·9	−23·9	47·8	2,375
25		22·9	22·9	45·8	4,986
26		21·9	21·9	43·8	11,636
27		18·2	18·2	36·4	31,586
28		16·3	16·3	32·6	94,311
29		14·3	14·3	28·6	161,262
30		13·4	13·4	26·8	464,786
31		12·4	12·4	24·8	636,500
32		11·5	11·5	23·0	3,930,150

SET III.

No. of Bar.	Material.	Maximum.	Minimum.	Range of Stress in tons per sq. in.	No. of Repetitions before Fracture.
33	Krupp's cast-steel axles.	+20·1	−20·1	40·2	55,100
34		17·2	17·2	34·4	127,775
35		16·3	16·3	32·6	797,525
36		15·3	15·3	30·6	642,675
37		15·3	15·3	30·6	1,665,580
38		15·3	15·3	30·6	3,114,160
39		14·3	14·3	28·6	4,163,375
40		14·3	14·3	28·6	45,050,640

[1] Not broken.

Fig. 110 shows the nature of the stress-cycle in Wöhler's machine (Fig. 109). In the diagram are marked the points of maximum skin stress—tension and compression, or + and— viz., MT_s and MC_s. At Z and Z^1, the stress is zero. Prof. Arnold[1] (in a paper from which the author has obtained much of the following information) quotes three sets of Wöhler's tests (p. 174). The first set has reference to wrought-iron of average statical maximum stress, 21·3 tons per sq. in.; the second set, on material called "homogeneous iron," was probably mild steel, or ingot iron, having a mean maximum stress of 28·2 tons per sq. in. The third set was probably made upon crucible steel of 0·6 per cent. carbon, with a mean maximum stress of 46·4 tons per sq. in.

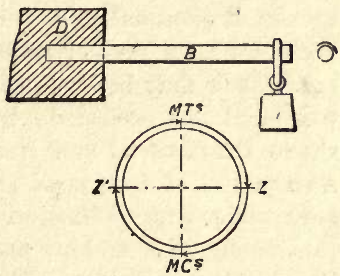


FIG. 110.—Diagram showing nature and Stress-Cycle of the Wöhler Test.

Arnold's Machine.—Prof. Arnold conceived the idea of bringing Wöhler's method into practical works use by greatly reducing the time occupied in making a test. He proposed to stress the material just beyond its elastic limit, and so reduce the time taken to make a test from hours to seconds. In Fig. 111 the nature of Arnold's test is shown. B is the test piece, $\frac{3}{8}$ inch diameter and about 6 inches long. It is gripped in the die D, and the stress is applied by the strokes of the slotted

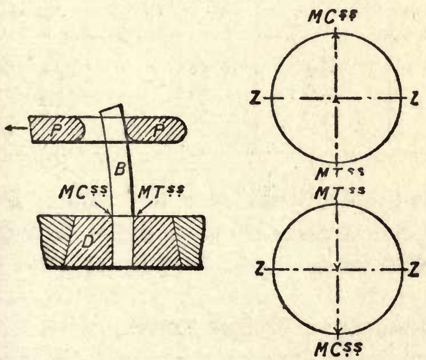


FIG. 111.—Diagram showing Nature and Stress-Strain Lines in Arnold's Test.

[1] Trans. Inst. N. A., 1909

plunger PP. A rate of alternation of 650 per minute is adopted. The diagrams show the alternation of the stress-strain lines in this test. Z is the fixed zero of stress. Theoretically the Wöhler test is perfect, while Prof. Arnold's is wrong; but nevertheless it gives valuable results concerning properties which Wöhler's tests do not reveal. No matter how dangerously brittle steel may be, from chemical or physical causes, if such treatment has produced a high elastic limit, the Wöhler test shows the material safe if stressed well short of that limit. As a matter of fact, such steel suddenly ruptures, sooner or later, under stresses theoretically quite safe. As an instance of this, results of some tests made on several steels by Mr. J. E. Stead, F.R.S., are given. There was a series of three sets with ascending phosphorus up to 0·5 per cent.—the last-named being most undesirable for engine parts. The analysis showed everything as being practically identical, except the phosphorus, which varies as shown in the table giving the results of static tests.

TABLE XV.—RESULTS OF STATIC TESTS.

Steel No.	Phosphorus. Per cent.	Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent. on 6 ins.	Reduction of Area. Per cent.
1	·041	20·4	33·1	23·0	52·0
2	·302	25·4	39·9	23·0	45·3
3	·509	32·0	44·0	20·0	45·3

The Wöhler tests made by Mr. Stead give the results set forth in the table below, the stresses being + and − 15 tons per sq. in., *i.e.*, a range of 30 tons.

TABLE XVI.—RESULTS OF WÖHLER TESTS.

Steel No.	Phosphorus. Per cent.	Reversals of Stress endured.	Ratio of Resistance to Alternating Stress.
1	·041	61,000	1·0
2	·302	167,300	2·7
3	·509	651,000	10·6

Prof. Arnold's tests—made by him at Sheffield University in complete ignorance of the nature of the steels—registered the figures embodied in the table below:—

TABLE XVII.—PROF. ARNOLD'S ALTERNATING STRESS TESTS.

Steel No.	Phosphorus. Per cent.	Alternations endured in Test No. (Under standard conditions.)			Ratio of Resistance to Alternating Stress.
		1.	2.	Mean.	
1	·041	258	284	272	100
2	·302	188	212	200	—
3	·509	72	128	100	37

Speaking in round numbers, the Wöhler test indicated that a mild steel containing 0·5 per cent. phosphorus was, with equal stresses, ten times as capable of resisting alternating stress as a steel containing 0·04 per cent. phosphorus. Prof. Arnold's test, on the other hand, indicated that a steel containing 0·5 per cent. phosphorus had about one-third the endurance of a steel containing 0·04 phosphorus. The curves of the yield points of the two alternating tests of the three steels show that the Wöhler curve is similar in type to that registered by the yield point or apparent elastic limit, Professor Arnold's curve being in an opposite direction and indicating what is well known to be the mechanical effect of phosphorus on steel.

The evidence supplied above seems to show that for practical purposes Prof. Arnold's test is the more useful.

Stanton's Alternating-Stress Testing Machine.—The principle of this machine is that of employing a rotating crank to cause periodic motion of a reciprocating mass by means of a connecting rod, the specimen under test forming the connection between the reciprocating mass and the crosshead. This device has been employed by Prof. Osborne Reynolds in the testing machine at Owens College, which is of the vertical type with a single balanced crank. In the National Physical Laboratory machine there are four cranks operating four

specimens, the motion of the specimens being in a horizontal plane. By this means the balancing of the machine is made independent of the ratio of the crank-arm to the connecting rod, so that a length of crank-arm has been adopted which enables experiments to be made at moderately low speeds, that is, from 600 to 1,000 revolutions per minute. Although this arrangement causes the motion of the specimens to deviate from the simple harmonic law, the effects on the stresses set up in the specimens are sufficiently small in value to be neglected, so that the maximum tensile force on the specimens may be taken as

$$\frac{W}{g}w^2r\left(1+\frac{r}{l}\right)\text{lbs.},$$

and the maximum compressive force on the specimens as

$$\frac{W}{g}w^2r\left(1-\frac{r}{l}\right)\text{lbs.},$$

where W = weight of mass attached to end of specimen in lbs.;
r = radius of crank pin;
w = mean angular velocity of crank-shaft;
l = length of the connecting rod.

It will be observed that the maximum tensile stress is 1·4 times the value of the maximum compressive stress, which is approximately the ratio of the stresses in the piston-rod of an ordinary reciprocating steam engine. The form of specimen adopted is the same as in Reynolds and Smith's experiments, consisting of a 5-inch bar screw cut $\frac{3}{21}$-inch Whitworth, and turned down in the centre to a diameter of $\frac{1}{4}$ inch for a length of $\frac{1}{2}$ inch. Great care has to be taken in the preparation of the specimens to ensure a gradual change of section in the turned-down part, as the effect of a change of section on the resistance of the specimen is much more marked in the case of tests under alternating stresses than in statical tests.

Prof. J. H. Smith's Alternating Tension and Compression Stress Machine.[1]—This machine, called by its

[1] *Engineering*, Vol. LXXXVIII., p. 105.

inventor a fatigue testing machine, was designed by Dr. J. H. Smith in 1904, but subsequently modified to its present form. In this machine, as in Stanton's, the load is produced by the centrifugal force of a rotating mass. Fig. 112 shows the general scheme of the apparatus employed. If we have two masses fixed to the ends of revolving arms which are pivoted at A and B, it is obvious that when the weights are at the top

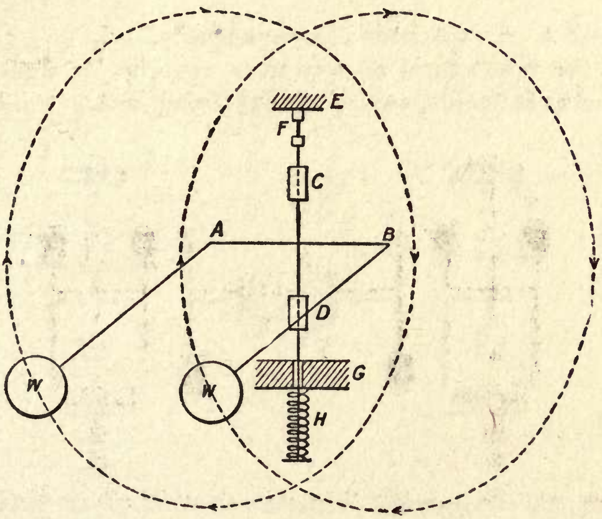


FIG. 112.—Diagram of J. H. Smith's Alternating Stress Machine.

of their motion they will pull the arm AB upwards with a force expressed by the usual formula

$$\frac{2WV^2}{gr}.$$

If now AB is rigidly attached to a vertical spindle passing through guides at C and D, and if we place a specimen F between the end of the spindle and a fixed mass E, then the specimen will be subjected to the force expressed above in compression. When the weights are at the bottom of their revolution the force on the specimen will be reversed. Suppose now we attach a spring H to the bottom of the spindle and

tighten this up so as to exert a force of S lbs. weight. Then the load on the specimen will vary between

$$\frac{2WV^2}{gr}-S \text{ and } \frac{2WV^2}{gr}+S.$$

By making S greater than

$$\frac{2WV^2}{gr}$$

the load on the specimen is always tensile.

In the latest form of apparatus used by Dr. Smith, the apparatus is double, two specimens being under test at one

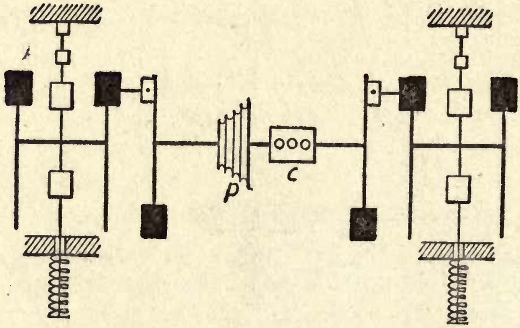


FIG. 113.—Diagram of J. H. Smith's Alternating Stress Machine.

time. Fig. 113 shows this arrangement, and it will be observed how two other masses are introduced for the purpose of balancing. P is a pulley, and C a counter. The specimens generally used are small, being only $\frac{1}{4}$ inch in diameter and $\frac{1}{2}$ inch long, but by introducing a special form of chuck lengths up to 4 inches can be used.

Fig. 114 gives an idea of the scheme as actually carried out in practice. The part shown is, as was explained previously, duplicated, and the whole machine runs in an oil bath. Referring to Fig. 114, there is, of course, no rigid connection at the point A, the arrangement consisting of a small slider working in guides. Otherwise part of the forces due to the

revolving weights would be taken up by the driving shaft.

The reader is referred to the article in *Engineering*,

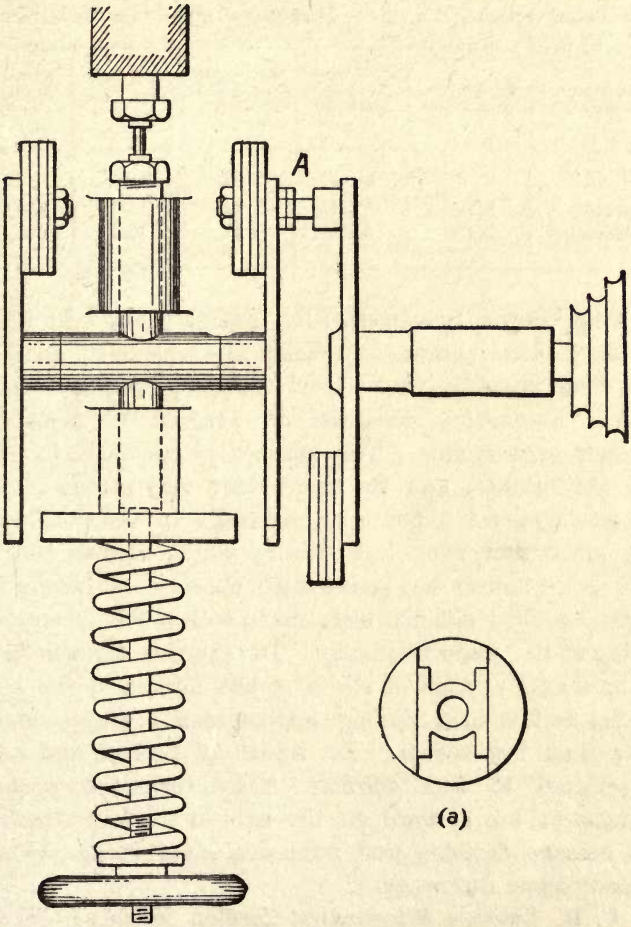


FIG. 114.—J. H. Smith's Alternating Stress Machine.

mentioned previously, for a full description, together with particulars of the very ingenious optical strain recorder and stress-strain oscillograph used.

The following are some results obtained by Dr. Smith on this type of machine:—

TABLE XVIII.

Oscillatory weight, 12·42 lbs. Diameter of specimen, ·2469 inch.

Set A. Mild Steel.	Revolutions per minute.	Maximum or Tensile Stress per sq. in.	Minimum or Compression Stress per sq. in.	Range of Stress per sq. in.	Number of Reversals before Rupture.
		Tons.	Tons.	Tons.	
Annealed .	2,126	7·99	7·11	15·1	248,700
Unannealed	2,122	8·03	7·17	15·2	226,500

A Ring-Shaped Specimen.—Dr. Stanton has very ingeniously devised an apparatus in which the specimen used is a ring. The latest annual report (1910) from the National Physical Laboratory contains an account of some high frequency experiments. The number of reversals has been 2,200 per minute, and the results are very satisfactory for hard steels (above 3 per cent. carbon). In the case of the softer steels and iron, indentations which weaken the ring occur. Dr. Stanton has successfully checked the results from his ring method against tests made with a Wöhler machine running at the same frequency. Dr. Stanton adheres to the opinion that the range of stress is not altered by the speed, and that neither iron nor high-carbon steel are worse at high speeds than low speeds. Dr. Smith, of Belfast, and others are opposed to this opinion. Since various independent investigators are at work on the subject we may soon hope for a definite decision and numerical data on the effect of frequency upon the range.

C. A. M. Smith's Alternating Torsion Machine.—Wöhler and other investigators have designed machines to work between + and − loads as already described. A machine has been designed by the author to do the same type of work, but the alterations are produced by loading a shaft so that a torque is applied. The stress is applied

by the inertia of a fly-wheel. The power is supplied by a small motor. Experiments have not yet been made with the apparatus, which is still in the course of construction. The chief practical difficulties appear to be those concerned

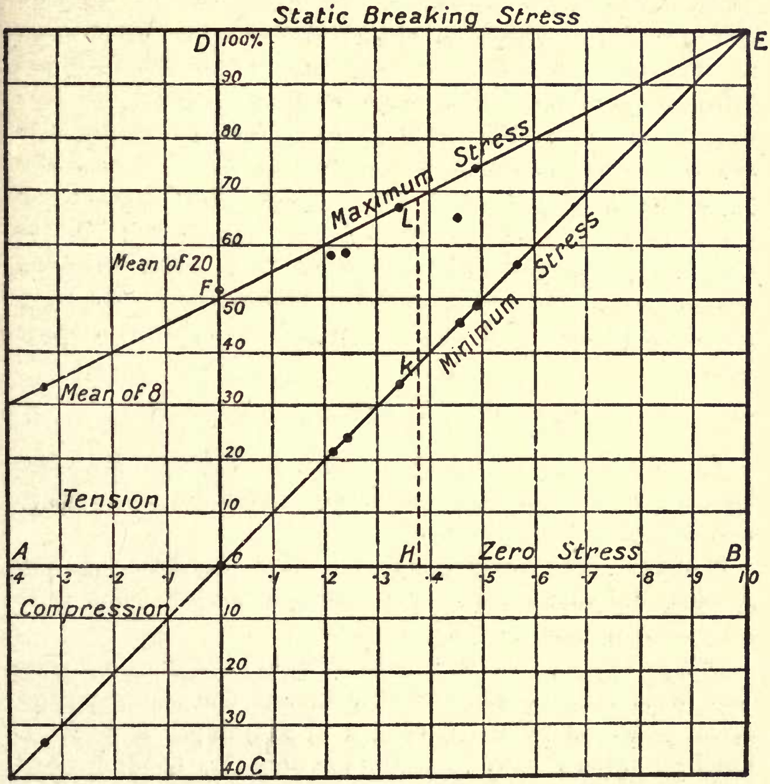


FIG. 115.—Curve for Rationalisation of Alternating Stress Experiments.

with obtaining balance so that there shall not be undue vibration at high frequencies. There is a minor difficulty of securing specimens to the grips, which would not occur but for the special design—for other purposes—of the specimens used.

Repeat Stresses.—Prof. Goodman has given a method of determining graphically the allowable maximum stress for a

given variation of stress, the statical breaking stress being given. Draw two ordinates A B (Fig. 115), C D set off O D to represent the statical breaking stress, and through O put in through E F. Then if *H k* is the minimum stress on the member, *H l* is the maximum load which can be repeated O E at 45° as a convenient slope, the horizontal scale being immaterial. Bisect O D and join indefinitely without breaking the bar. The stress scale is marked in percentage of the static breaking load. The points indicate the results of experiments by Wöhler, Spangenberg, and Bauschinger, and it will be observed that theory and experiment coincide as closely as can reasonably be expected. Expressed algebraically we have, when designing a member which will be subjected to both a steady load W_{min} and a fluctuating load ($W_{max.} - W_{min.}$), the equivalent static load.

$$W_O = W_{min.} \mp 2\,(W_{max.} - W_{min.})$$

The *plus* is used when both the loads act together, *i.e.*, when both are tension or both compression, and the *minus* when they act against one another.

Sankey's Hand Bending Machine.—This machine has been specially designed for the rapid testing of material, and is in a convenient form for use in works.

The principle on which it is based is to bend the test piece backwards and forwards until it is broken, the bending effort being measured by the deflection of a spring. A device is fitted for automatically recording not only this bending effort for each bend, but also the number of times the specimen can be bent without rupture, as well as the total energy required to break it. A diagram is obtained, the form of which shows at a glance the quality of the material.

The machine gives most of the information needed in the workshop as regards the strength of the material in respect of static stresses, and hence compares not unfavourably with the more lengthy and expensive tensile tests ; but, in addition, it exhibits in a striking manner what, for want of a better

word, may be called the "leatheriness" of the material, or, in other words, its power to resist the effect of alternations of stress, that is to say, "fatigue."

One bend is defined as bending the test piece from the extreme position on the right to the extreme position on the left, or from the extreme position on the left to the extreme position on the right.

The machine is illustrated in Fig. 116, and consists of a small bed-plate, arranged to bolt down to a bench, at one corner of

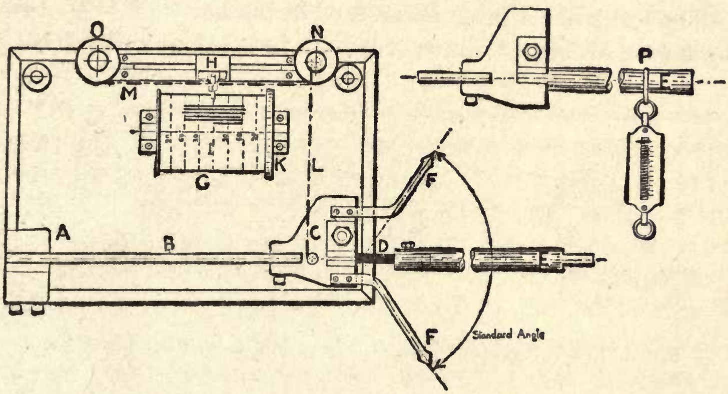


FIG. 116.—Sankey's Hand Bending Machine.

which there is a grip A for securing one end of a flat steel spring B. The other end of the spring is fitted with a special grip C for holding one end of the test piece D. The other end of the test piece is fixed into a handle E, about 3 feet long, by means of which it is bent backwards and forwards through the "standard" angle. An indicator F is provided to show this standard angle. Alongside of the spring, and fixed to the bed-plate, there is a horizontal drum G to carry the recording paper, and the pencil H has a horizontal motion actuated by the motion of the grip C and conveyed by the steel wires L and M and the multiplying pulley N, the wires being kept taut by the spring box O. The zero line is in the middle of the paper, and the pencil H moves in one direction when the bending

is from right to left, and in the opposite direction when it is from left to right. The drum has a ratchet wheel K with a detent (not shown) worked by the motion of the pencil carrier. The result of the combined motion of the pencil and of the drum is to produce an autographic diagram such as shown in Fig. 117. Obviously the greater the stiffness of the test piece the more the flat spring B will have to be bent before its resistance is equal to the resistance to bending of the test piece. Hence the motion of the pencil is proportional to the effort required to bend the test piece.

The test piece is properly secured in the handle E (Fig. 116) by means of the set screw, it is then inserted into the grip C,

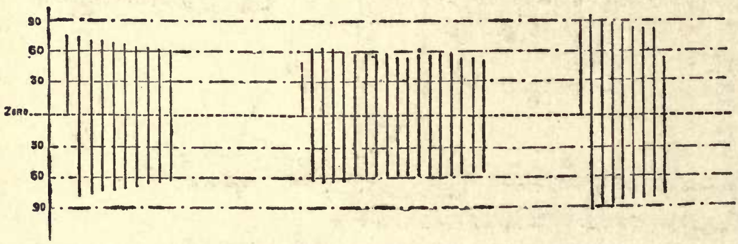


FIG. 117.—Autographic Diagram from Hand-bending Machine.

and the free length ($1\frac{3}{4}$ inches) is adjusted by means of a gauge provided for the purpose, after which the grip C is tightened. The first bend is taken to the left until the mark on the handle coincides with the pointer indicating the "standard" angle. The bending is then reversed, and the test piece is bent until the mark on the handle coincides with the second pointer. The bending is again reversed, and so on until the specimen breaks. The point at which the test piece breaks should be noted in decimals of one bend, which are marked on the indicator.

The "standard" angle is so fixed that the distance travelled along the arc of the circle 1 foot radius from the point of bending the test piece is 1·60 ft. (this angle is $91\frac{1}{2}°$). Hence by multiplying the bending effort (in lbs.) by 1·6 the energy (in ft. lbs.) required to make a complete bend is found.

Generally, the stronger the material the less the number of bends it will endure, and approximately it may be taken that, in the case of mild steel, the bending effort of the first bend is proportional to the yield stress in tension of the material. It has been found by experience that with the standard test piece ($\frac{3}{8}$ inch diameter), one half of the bending effort in ft. lbs. is nearly equal to the yield stress in tons per sq. in. This rule is only approximate, but it will give a fair idea of the strength of the material as expressed in the ordinary way. The number of bends is proportional to the ductility of the material, and experiment shows that this number is approximately proportional to the elongation multiplied by the reduction of area in a tensile test.

The area of the autographic diagram represents the energy required to break the test piece. The recording gear has been so proportioned that 1 sq. in. of this diagram is equivalent to 400 ft. lbs. The area in question can be obtained by means of a planimeter, but it can also be approximately arrived at by estimating the average bending effort, and multiplying by 1·6 times the number of bends. 1·6 times the number of bends must be taken, because, as already pointed out, the arc swept by the point of application of the bending effort (in ft. lbs.) is 1·60 foot for each bend. This energy figure gives valuable information as to the quality of the material, and for machinery steel should not be less than 2,500 ft. lbs., but for the steel used in petrol engines and the like a higher figure is desirable, say 3,500 to 4,000 ft. lbs.

Many trials show that with steel in a normal condition the first bending effort is always distinctly less than the second bending effort (see Fig. 117). But if the steel has been artificially stiffened by drawing or hammering, the first bending effort is the greatest (see Fig. 117). In fact, the effect of the bending is to undo the artificial stiffening. This is a valuable and unique property of this testing machine.

Fractures.—The following is a short list of the fractures,

with this machine, obtained with steels of good quality, and the probable inferences to be drawn therefrom:—

Fractures.	Probable Inferences.
Silky	Mild steel, nickel steel.
Granular	Medium carbon steel.
Fine crystalline	High carbon steel.
Granular and crystalline ...	Mild and medium carbon steels when overheated.
Coarse crystalline... ...	Mild and medium carbon steels when overheated, and then hammered at too low a temperature.

Effect of Speed.—Some interesting results have been obtained by Mr. E. M. Eden[1] on a machine of the rotating beam type, in which the specimen is subjected to a bending moment and no shear. Five materials were tested at speeds of about 300, 600 and 1,300 v.p.m. Within the range of the experiments the endurance is independent of the speed at which the machine is run. The apparatus is comparatively simple and seems suitable for college laboratories. The disagreement of various experimenters using different methods of obtaining alternating stress shows that the subject is not yet exhausted. Work has also been done by Bairstow[2] and Howard.[3]

[1] Univ. of Durham Phil. Soc., Proc. 1909—10.
[2] Phil. Trans. Royal Society, December, 1909.
[3] International Association for Testing Materials, 1909.

CHAPTER X

THE TESTING OF CEMENTS, REINFORCED CONCRETE, AND STONES

After mild steel, the above are probably the most important materials of construction; all of them are very variable in their properties, and much depends on the method of testing. In the case of Portland cement we have given an outline of the methods laid down by the Engineering Standards Committee, and as so much depends on method, it is important to follow this method as closely as possible where comparative results are desired. It will be noted that even the rate of loading may considerably affect the results. Table 21 gives an idea of results obtained at different rates of loading.

In the case of reinforced concrete, only those results obtained on full size constructional members or pieces of work can be considered as giving reliable results, hence we have refrained from giving results of tests except such as give what may be considered the fundamental properties, *i.e.*, the co-efficient of elasticity, the adhesive force of iron bars, and the crushing strength, together with an account of a full size test on a floor.

The Testing of Cements and Concretes.

The standard method of testing Portland cement is laid down by the British Engineering Standards Committee[1] as follows:—

Fineness and Sieves.—The cement shall be ground to comply with the following degrees of fineness, viz.:—

Residue on sieve 76 × 76 meshes per sq. in. not to exceed 3 per cent.

[1] The Committee's actual specification (Report No. 12. Revised August, 1910 British Standand Specification for Portland Cement) should be consulted for tests intended to comply in detail with their recommendations.

Residue on sieve 180 × 180 meshes per sq. in. not to exceed 18 per cent. [Sieves as per British Standard Specification.]

Specific Gravity.—Not less than 3·15 when fresh burnt and ground, and not less than 3·10 if cement has been ground for not less than four weeks.

Chemical Composition.—[See British Standard Specification].

Mode of Gauging.—The cement shall be mixed with such a proportion of water that after filling into the mould the mixture shall be plastic. Fresh water to be used at a temperature between 58° and 64° F. A suitable form of mould designed to give a form of briquette to the dimensions shown in Fig. 118 to be filled with the cement without mechanical ramming and allowed to stand on a non-porous plate until the cement sets. As soon as the briquette can be removed without injury, this should be done, and the briquette kept in a damp atmosphere for twenty-four hours, after which it should be kept in a bath of clean fresh water between 58° and 64° F., and allowed to remain there until breaking, the water to be changed every seven days.

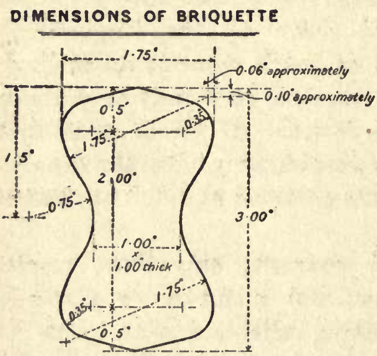


FIG. 118.—Dimensions of Standard Briquette (British Standard Specification).

Testing.—Twelve briquettes should be prepared for each test—six to be broken after seven days, and six after twenty-eight days. The usual type of machine for testing the specimens is described below. When testing with standard sand, the latter to be obtained from Leighton Buzzard, and according to the British Standard Specification. The Committee lay down the following tensile strengths as the *minimum* allowable.

Neat Test.—(Average of six specimens.)

7 days from gauging . . 400 lbs. per sq. in.

Sand Test.—(Average of six specimens) (3 parts sand, 1 cement.)

7 days from gauging . . 150 lbs. per sq. in.

Setting Time.—Cement is said to be set when on gently

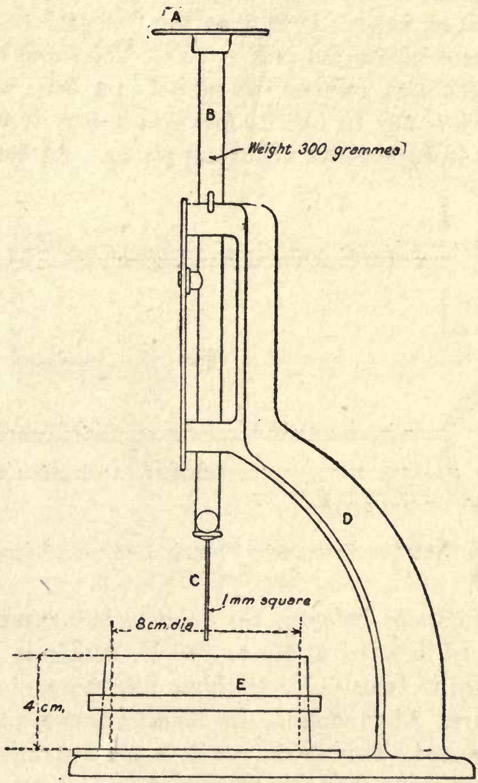


FIG. 119.—Setting Needle for Cement (British Engineering Standards Committee's suggestion).

applying the "needle" of the instrument illustrated in Fig. 119 no impression is made in the surface. The following times of setting define the terms slow, medium, and quick setting :—

Quick.—Final setting time not less than 10 nor more than 30 minutes.

Medium.—Final setting time not less than 30 nor more than 120 minutes.

Slow.—Final setting time not less than 120 no more than 300 minutes.

Soundness.—The standard method of testing for soundness is by means of what is known as the "Chatellier test," using the apparatus illustrated in Fig. 120. The small brass mould is filled with neat cement and placed in a bath of water at a temperature of 58° to 64° F. for twenty-four hours, the two open ends being covered with glass plates. At the end of this

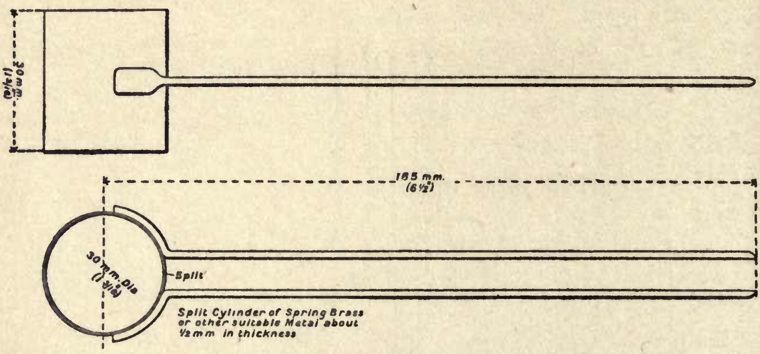


FIG. 120.—Le Chatellier Soundness Testing Instrument (British Standard Specification).

time the distance between the pointers is measured, and the mould placed in water at 58° to 64° F. which is brought to boiling point in twenty-five to thirty minutes and kept boiling for six hours. After cooling, the distance between the points is again measured. This distance will be found to have increased, and it is laid down that this expansion must in no case exceed 10 millimetres after twenty-four hours aeration, or, if the above test has failed, 5 millimetres after seven days aeration.

Cement Testing Machine.—The simple form of machine, shown in Fig. 121, is used for testing cement and concrete in tension. As the strength of these materials in this direction is very small, the machine used is of a correspondingly small size, and is much simpler than those used for testing metallic specimens. The cement is first moulded into the form of a briquette, such as is shown in the figure, and is such that the

smallest section of the specimen is 1 inch square. The briquette is held in well-greased jaws of the form shown in Fig. 121. The lower of these is capable of being moved vertically by means of a hand-wheel and screw which are not shown in the diagram. The upper jaw is connected to a point B on the lever A C, whose fulcrum A is attached to the frame of the machine G. The outer end C is connected by a rod C D to the short arm of the lever D F, whose fulcrum is at E. The length of C D is made adjustable so that the lever D F may be in a horizontal position at the beginning of the test.

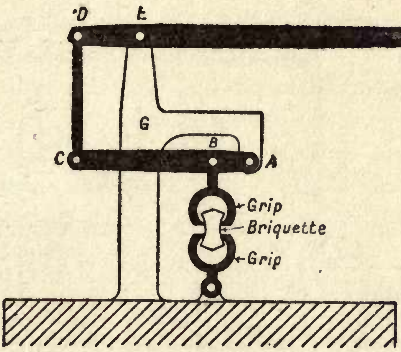


FIG. 121.—Cement Testing Machine.

The load is applied by means of a variable weight H which is fixed to the end F of the lever D F. In one type of this machine the weight H consists of an iron pan into which lead shot is poured at a constant rate, so that the load uniformly increases by 100 lbs. in every 12 seconds. When the specimen breaks the pan of shot drops on to a movable lever which it depresses, thereby automatically cutting off the supply of shot. The shot is then weighed and the strength of the cement calculated by means of the known leverages in the machine.

The Bailey machine for cement testing has only a single lever, from the short end of which the specimen is gripped in the same way as in the machine just described. The long end, however, supports a long cylindrical vessel into which water is flowing from a tank above the lever during tests. The

load is thus applied as before, at a uniform rate. When the specimen breaks the downward movement of the long arm of the lever is utilised to automatically cut off the supply of water. A scale is provided on the water vessel, and is so divided that the height of water in the vessel gives the breaking load of the specimen as a direct reading.

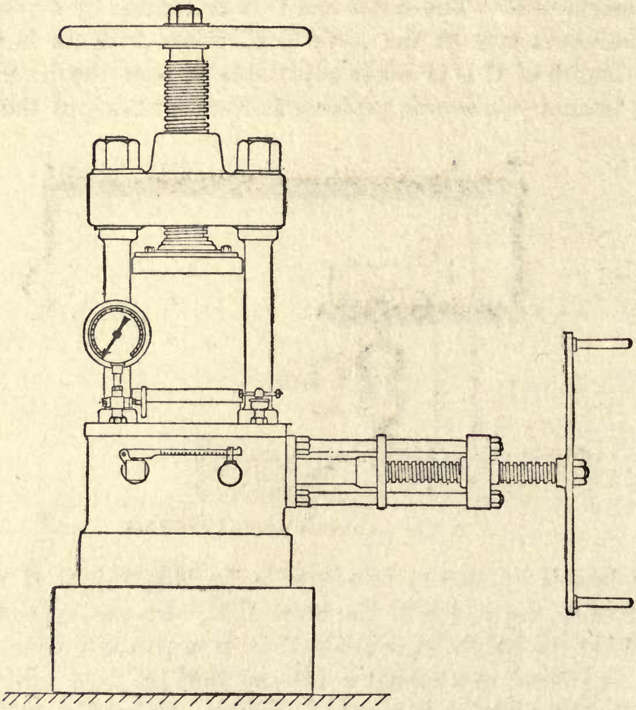


FIG. 122.—Machine for Compression Tests of Stones and Cements.

Compression.—The resistance of concrete to compression is usually determined by crushing cubes of 4, 6, 8, or 12-inch sides at some stated age. The strength per sq. in. will in general decrease with the size of the cube. The crushing load may be obtained in any ordinary testing machine provided with compression plates or, where much of this class of work has to be done, on a machine specially built for cement testing. These special machines in general consist of

an ordinary hydraulic press, but worked with oil or glycerine, in which the piston friction is so far reduced that a gauge attached to the main cylinder may be made to read the crushing load direct. This gauge must be so constructed that after the material fails the pointer will still indicate the maximum pressure, as failure generally takes place suddenly and without previous cracking of the material. Messrs. Bailey make such machines, capable of exerting a crushing load of 12, 60, and 150 tons respectively. It is most important in the testing of cements, concretes, stones, etc., that the bedding should be absolutely even, as otherwise splitting at the highest corner will take place. To ensure this even bedding plaster of Paris is generally used. The compression plates are first cleaned and then slightly oiled. A thin paste of plaster is then put on the lower plate about a quarter of an inch thick. The block is carefully bedded on to this and another quarter of an inch put on top of the block. A small amount of pressure is then applied, and the machine allowed to stand until the plaster is set, say, in about five to ten minutes.

Loading should be applied slowly and evenly till fracture occurs, which in homogeneous material tends to take place by shear at 45°, thus forming cones in the case of cylinders, or pyramids in the case of cubes.

Both the tensile and compressive strength are very variable, especially the former. The chief conditions which determine the strength are :—

1. Proportion of ingredients.
2. Quality of ingredients.
3. Amount of water used.
4. The method and amount of mixing.
5. Amount of consolidation effected.
6. The form of the piece.
7. Atmospheric conditions during hardening.
8. Time after gauging.
9. Manner and speed of applying load.

The following tables of experimental results will illustrate the effect of the above :—

TABLE XIX.—DIFFERENT SAMPLES OF PORTLAND CEMENT (each reading mean of about five briquettes).

Cement.		Fineness. Per cent. Passing.		Tensile Strength, in lbs. per sq.																
				Neat Cement.					1 part Sand to 1 Cement.					3 parts Sand to 1 Cement.					4 parts Sand to 1 Cement.	5 parts Sand to 1 Cement.
Brand.	Sample.	Sieve No. 100. Holes ·0065 in. square.	Sieve No. 120. Holes ·0046 in. square.	7 Days.	28 Days.	6 Months.	2 Years.	5 Years.	7 Days.	28 Days.	6 Months.	2 Years.	5 Years.	7 Days.	28 Days.	6 Months.	2 Years.	5 Years.	2 Years.	2 Years.
H	5 S	—	—	497	570	619	633	668	501	650	740	768	749	176	272	456	398	384	—	—
H	21 S	90·7	82·6	567	710	736	703	804	566	669	722	840	802	197	266	434	395	350	283	228
R	300 S	—	—	523	619	717	676	768	525	591	756	813	746	202	255	384	394	370	280	224
I	8 S	89·5	76·4	469	562	669	748	719	486	563	727	796	725	177	250	387	388	390	—	215
P	2	—	—	516	626	721	638	741	467	653	752	814	728	148	251	381	388	365	268	—
K	3	81·3	67·7	518	628	646	643	745	477	606	722	860	778	164	237	367	383	354	—	—
F	4	86·7	79·0	387	575	685	728	723	404	614	761	855	793	101	212	385	379	382	—	—
C	12 S	86·6	76·0	532	711	797	790	751	502	621	756	687	620	144	219	362	376	332	233	—
N	18 S	83·0	70·4	403	479	574	637	604	399	546	650	649	719	133	185	311	351	318	—	—
J	17 S	89·0	79·1	574	743	737	767	745	503	665	743	764	722	181	261	392	350	343	249	—
A	20 S	84·5	73·8	556	637	691	681	698	498	616	675	795	737	150	227	374	350	327	—	198
G	1	92·0	80·0	542	616	732	730	762	469	560	661	704	672	175	240	338	333	311	—	184
Sum				6,084	7,476	8,324	8,374	8,728	5,798	7,354	8,665	9,345	8,791	1,948	2,874	4,571	4,485	4,226	—	—
Mean				507	623	694	698	727	484	613	722	779	733	162	240	381	374	352	—	—

TABLE XX.—EFFECT OF TIME WHEN APPLYING LOAD.[1]

Rate of Applying Stress. Pounds per Min.	Tensile Strength obtained. Pounds per sq. in.
50	400
100	415
200	430
400	450
6,000	493

TABLE XXI.

Cement.	Proportions.	Age of Briquettes.	Tensile Strength. Pounds per sq. in. for stress applied at rate of pounds per minute.				
			100	300	500	700	900
Portland	Neat cement	7 and 14 days	453	485	521	520	528
,,	Ditto	3 months	—	590	617	622	640
,,	1—2	3 months	445	467	487	507	510
Natural	Neat cement	7 days	150	169	186	—	202
,,	Ditto	3 months	309	351	363	378	390
,,	1—2	3 months	255	299	327	329	354

TABLE XXII.—EFFECT OF PROPORTION OF SAND.
H and R are two samples of Portland Cement.
Sand used, River Sand, "Point-aux-Pins."

Parts Sand to 1 Cement by Weight.	Tensile Strength, lbs. per sq. in.					Proportionate Strength, Two years if 1—2=100.
	6 Months.		2 Years.			
	H	R	H	R	Mean.	
2	512	504	534	548	541	100
3	390	335	363	355	359	66
4·09	295	261	296	288	292	54
6	175	144	191	174	182	35
8	113	96	132	132	132	24
10	64	74	104	116	110	20

[1] The rate of loading specified by the B.E.S.C. for testing Portland cement is 100 lbs. in 12 seconds, *i.e.*, 500 lbs. per minute.

TABLE XXIII.—COMPRESSIVE STRENGTH OF CONCRETE.

Mean results with four brands Portland Cement, illustrating effects of Proportions, Consistency, and methods of Storage. Tests of Concrete Cubes, about 12 months old, made for State Engineer of New York.

Parts Sand to one Cement—Vol.		2		3		4		Means.		
Vol. Meter as per cent. of Vol. Loose Aggregate.		33	40	33	40	33	40	33 and 40.		
Storage of Cubes.	Consistency.	Crushing Strength, lbs. per sq. in.						Proportional.		
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*
Water 3 to 4 months, then buried in sand.	Moist earth	3,632	3,785	2,506	2,482	1,914	1,989	2,718	100	—
	Mason's	3,094	3,516	2,459	2,354	1,886	1,928	2,540	94	—
	Quaking	3,111	3,116	2,234	2,318	2,015	1,794	2,431	89	—
	Mean	3,279	3,472	2,400	2,385	1,938	1,904	2,563	—	100
Covered with burlaps and kept wet for several weeks, then exposed to weather.	Moist earth	2,557	3,176	2,194	2,126	1,674	1,728	2,242	100	—
	Mason's	2,591	2,909	1,860	1,930	1,643	1,678	2,102	94	—
	Quaking	2,648	2,912	1,856	1,925	1,855	1,548	2,124	95	—
	Mean	2,599	2,999	1,970	1,994	1,724	1,651	2,156	—	84
In cool cellar.	Moist earth	3,053	3,006	2,004	2,012	1,743	1,612	2,238	100	—
	Mason's	2,529	2,846	1,980	1,829	1,510	1,679	2,062	92	—
	Quaking	2,488	2,554	1,711	1,965	1,714	1,625	2,010	90	—
	Mean	2,690	2,802	1,898	1,935	1,656	1,639	2,102	—	82

NOTE.—Moist earth, Mason's, Quaking, indicate increasing percentage of water used in mixing.

TABLE XXIII.—*Continued.*

Part Sand to one Cement—Vol.		2		3		4		Means.		
Vol. Meter as per cent. of Vol. Loose Aggregate.		33	40	33	40	33	40	33 and 40.		
Storage of Cubes.	Consistency.	Crushing Strength, lbs. per sq. in.						Proportional.		
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*
Fully exposed to weather.	Moist earth .	2,515	3,054	1,910	2,078	1,614	1,593	2,127	100	—
	Mason's . .	2,606	2,746	1,983	1,930	1,554	1,564	2,064	97	—
	Quaking . .	2,459	2,724	1,793	1,908	1,682	1,529	2,016	95	—
	Mean . . .	2,527	2,841	1,895	1,972	1,617	1,562	2,069	—	81
Mean results, four methods of storage.	Grand Means .	2,774	3,028	2,041	2,072	1,734	1,689	2,223	—	—
	Ratios . .	$\frac{2,774}{3,082}$	= 91·6%	$\frac{2,041}{2,072}$	= 98·5%	$\frac{1,734}{1,689}$	= 102·6%	—	—	—
								—	—	—
								—	—	—
Mean results, four methods of storage and two percentages of mortar.		Str.	Prop.	Str.	Prop.	Str.	Prop.			
	Moist earth .	3,097	100	2,164	100	1,733	100	2,331	100	—
	Mason's . .	2,854	92	2,040	94	1,680	97	2,192	94	—
	Quaking . .	2,751	89	1,964	91	1,720	99	2,145	92	—

NOTE.—Moist earth, Mason's, Quaking, indicate increasing percentage of water used in mixing.

The Application of Brinell's Ball Test to Cement Testing. —*La Revue de Métallurgie* and *Le Genie Civil* have recently published articles dealing with the testing of cement and concretes of all kinds by means of Brinell's Ball test.

A rough and ready method of a similar nature has long been

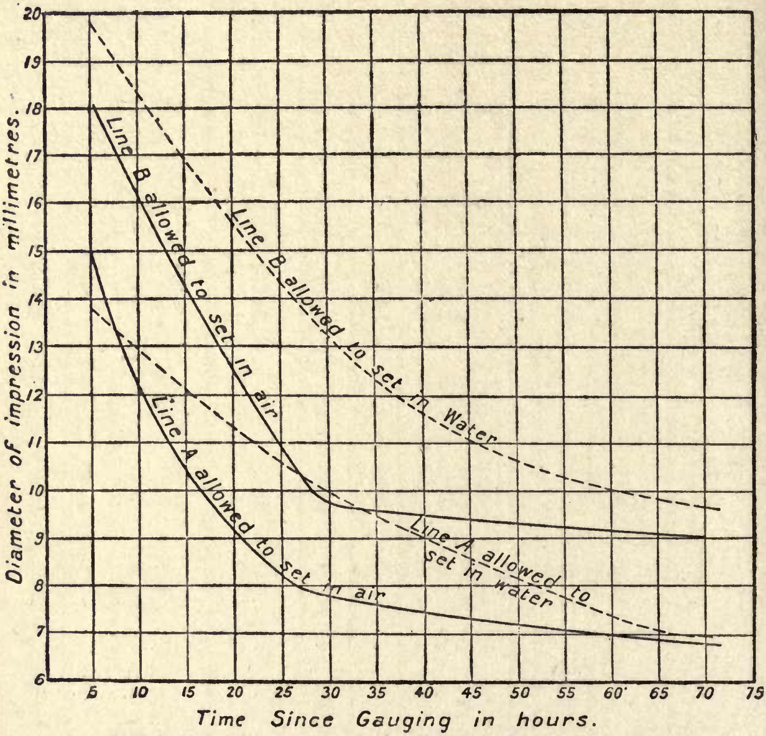


FIG. 123.—Tests on Cement with Brinell's Ball Test.

in use for the rapid testing of cements as to their setting properties; it consists, in fact, of observing how long the hardening must be allowed to continue before it becomes impossible to make any considerable mark on the surface by pressing on the sample with the thumb; exerting a force of perhaps 20 to 30 lbs. Such a method has, of course, no scientific pretensions, as has the following :—

The sample is prepared with a smooth surface by flattening

it with a sheet of glass while it is in the mould. The exact dimensions of the mould do not appear to affect the result, but it is essential that the specimen should not be less than 2 to $2\frac{1}{2}$ times the depth of the deepest impression likely to be made, and of sufficient surface area so that the impression does not have to be made too near the edge, as in that case cracking is likely to take place, or otherwise unsatisfactory results obtained. The size of ball suggested as giving the best results is 3 centimetres in diameter, and is pressed, after being slightly wetted, on to the surface partly by the weight of the apparatus itself and partly by adding lead discs. From 1 to 20 kilos. (2·2 to 44·0 lbs. approximately) is the total load used for new samples, although for old material 700 to 800 kilos. (1,540 to 1,760 lbs.) pressure is sometimes necessary for very hard specimens.

The load having been applied for a short time, say nine or ten seconds, the apparatus is removed and the spherical area of the depression measured. This latter is found to be practically proportional to the weight and to the fifth root of the radius of the ball employed.

For a given or fixed diameter of ball

$$\text{C (the hardness number)} = \frac{\text{Weight in kilogrammes.}}{\text{Spherical surface in sq. cms.}}$$

Or for different size balls

$$\text{C}\sqrt[5]{\text{Radius}} = \text{Constant.}$$

It will be noted that the latter is the same as for the metals.

It is obvious that cements will not give such a clear impression as metals do, so that even when using a microscope it is found difficult to obtain very reliable readings after about 90 days' setting, but below that time very consistent results appear to have been obtained.

The curves in Fig. 123 show how the diameter of the impression varies with the time of setting with a constant load. The samples were two hydraulic limes denoted by the letters A and B.

Tests in Connection with Reinforced Concrete.

Determination of Young's Modulus.

Table XXIV.—Experiments by Professor Hatt

Proportions of the Concrete.					Age, days.	Ec.	Stress where Measured, lbs. per sq. in.	Crushing Stress, lbs. per sq. in.
Cement.	Sand.	Broken Stone.	Gravel.	Cinders.				
1	2	4	—	—	9	$4 \cdot 70 \times 10^6$	750	2,880
1	2	4	—	—	9	$3 \cdot 94 \times 10^6$	1,500	
1	2	4	—	—	14	$4 \cdot 34 \times 10^6$	750	2,575
1	2	4	—	—	14	$3 \cdot 68 \times 10^6$	1,500	
1	2	—	—	4	9	$5 \cdot 58 \times 10^5$	—	495
1	2	—	—	4	9	$5 \cdot 53 \times 10^5$	—	595
1	2	—	—	4	7	$6 \cdot 30 \times 10^5$	—	416
1	—	—	5	—	6	$2 \cdot 09 \times 10^6$	—	1,185

Table XXV.—Adhesive Force on Rods (Hatt).[1]

Diameter of Rod in Inches.	Age of Specimen, in Days.	Depth of Rod in Concrete.	Adhesion in lbs. per sq. in. in Nominal Surface.		
			Maximum.	Minimum.	Mean.
$\frac{7}{16}$	32	72	735	470	636
$\frac{5}{8}$	35	76	780	714	756

[1] These results are somewhat higher than those usually obtained. The following, by Prof. Warren, of Sydney University, were performed with prisms of concrete 12 inches long and 4 × 4-inch section. Concrete mixed 1 : 3 and and 1 : 2 : 2 stone being broken to $\frac{3}{4}$ inch gauge. Bars of Bessemer steel $\frac{5}{8}$ inch diameter.

TABLE XXVI.

Description.	Composition.				Age in Days.	Adhesion in lbs. per sq. in. of surface.	
	Cement.	Sand.	$\frac{3}{4}$ Shives.	Water, per cent.			
Bars with natural skin on. Hardened in air.	1	3	—	12	45	216·5	Mean, 198.
	1	3	—	12	45	221·0	
	1	2	2	10	45	184·5	
	1	2	2	10	45	170·0	
Bars cleaned with emery paper. Hardened in air.	1	3	—	12·5	45	118·0	Mean, 125.
	1	3	—	12·5	45	72·0	
	1	2	2	10	44	154·0	
	1	2	2	10	44	155·0	
Bars cleaned with emery paper. Hardened in water.	1	3	—	12	45	154·0	Mean, 185.
	1	3	—	12	45	191·0	
	1	2	2	10	45	204·0	
	1	2	2	10	45	191·0	

The Testing of Ferro-Concrete Beams.—The Amsler-Laffon beam testing machine, which has been specially designed for the cross-breaking tests on beams, is illustrated in outline in Fig. 124. A is a cylinder in which fits a ram B, the accuracy of the fitting being such that no packing is required when castor oil is used as the pressure medium. D is the beam which can be loaded by a single concentrated load or in two places, as shown in Fig. 124, in which latter case the stress distribution approximates to that obtained with a uniformly distributed load. The length of the beam is between the bearings at G and H. At these points the beam is held down by rods which pass underground and are attached to the main framework. It will be seen that by this means the tension side of the beam is on top. The arrangement for measuring defections is fairly obvious from the illustration. J is a light wooden cross beam supported by suitable attachments from either end fixed on the neutral axis of the beam. By means of the levers MN and NQ the motion of M, which is

attached to the neutral axis of the beam, is magnified on a scale P attached to the cross-beam J. The loads are applied by forcing oil into the cylinder A by means of a rotary pump. Owing to there being no packing, and consequently very slight friction, loads can be measured by observing the readings of a pressure-gauge connected to the cylinder.

Such an arrangement is very suitable for carrying out tests on ferro-concrete beams, and much useful research has been performed on a machine of this type at the Manchester School

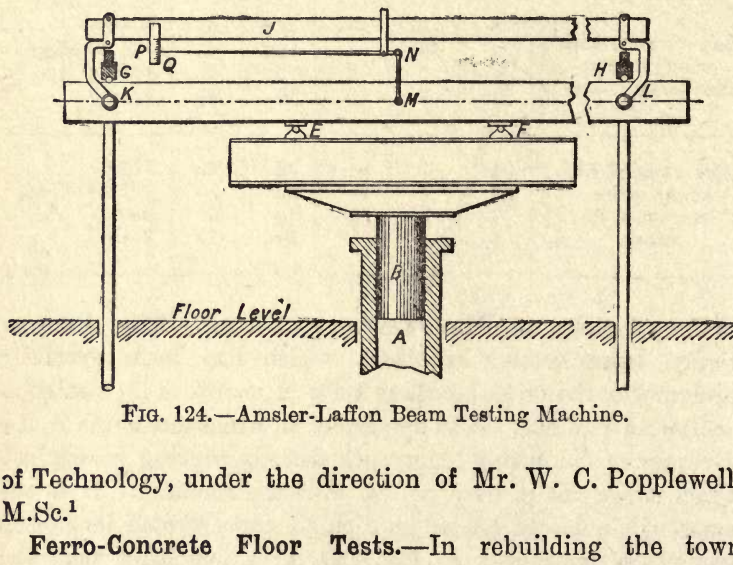


FIG. 124.—Amsler-Laffon Beam Testing Machine.

of Technology, under the direction of Mr. W. C. Popplewell, M.Sc.[1]

Ferro-Concrete Floor Tests.—In rebuilding the town mansion at the corner of Grosvenor Square and North Audley Street the architects, Messrs. Read and Macdonald, of Cork Street, W., decided to construct all the floors of ferro-concrete, partly for structural reasons and partly because of the valuable fire-resisting qualities of ferro-concrete. On April 10th, 1907, and the succeeding five days, a careful series of load tests was made by Messrs. Holloway Bros., the building contractors, under the direction of the architects. The area selected for the purposes of the tests was a portion of the first floor,

[1] "Proc. Inst. Civ. Eng.," vol. clxxvii., pp. 3—18.

consisting of a 3-inch slab, measuring 19 feet 6 inches long by 13 feet 3 inches wide, and carried by two beams projecting 6 inches below the under surface of the slab by 8 inches wide, and having the clear span of 19 feet 6 inches between the supports. In order to provide for the exact registration of deflection, three instruments were placed beneath one of the beams: one at the middle of the

FLOOR TESTS AT GROSVENOR SQUARE.

Date.	Time.	Load, lbs. per sq. ft.	Deflection in Fractions of an Inch.		
			Left Hand.	Right Hand.	Centre.
April 10, 1907 .	—	0	0	0	0
,, ,, ,, .	—	100	0·0355	0·0355	0·11
,, ,, ,, .	—	130	0·055	0·051	0·15
,, ,, ,, .	2.50 p.m.	159	0·079	0·083	0·216
,, ,, ,, .	3.10 ,,	159	0·079	0·083	0·22
,, ,, ,, .	3.25 ,,	130	0·071	0·077	0·193
,, ,, ,, .	3.45 ,,	100	0·055	0·063	0·161
,, 11, ,, .	7.45 a.m.	100	0·063	0·067	0·165
,, 12, ,, .	2.45 p.m.	100	0·067	0·071	0·173
,, ,, ,, .	3.0 ,,	72	0·043	0·055	0·157
,, ,, ,, .	3.15 ,,	42	0·043	0·047	0·126
,, ,, ,, .	3.45 ,,	13·5	0·027	0·037	0·095
,, ,, ,, .	4.15 ,,	0	0·016[1]	0·023	0·063
,, 13, ,, .	9.0 a.m.	0	0·016[1]	0·012	0·051
,, 14, ,, .	12 noon	0	0·016[1]	0·008	0·043
,, 15, ,, .	11.50 a.m.	0	0·008	0·000	0·043[1]

[1] Instrument has probably been disturbed.

span and the other two at the distance of 2 feet 9 inches from the supports. Loading was effected by means of bricks and Portland cement in bags. The results of the tests are summarised in the subjoined table, from which it will be seen that the maximum deflection under double the normal superload of 84 lbs. per sq. foot was only 0·139 inch, calculated over the central 14-foot portion of the beam, or $\frac{1}{1210}$ of the span No records were taken of the settlement at the supporting walls, so it would not be fair to regard the maximum deflection of 0·22 inch as having taken place in the floor itself. But

adopting that value for the sake of argument, it will be seen that the proportion is only $\frac{1}{1060}$ of the entire span, or less than one-half the proportion generally allowed by architects. Another point worthy of special note is that on removal of the loading the floor returned practically to its original form, thereby demonstrating the perfect elasticity of the construction.

Stones, Bricks, etc.—These materials are tested in compression in a similar manner to that described for cements. The following table indicates some results of such materials taken from Popplewell's "Testing of Materials of Construction":—

TABLE XXVII.—CRUSHING STRENGTH OF VARIOUS STONES, ETC.

Material.	Authority.	Crushing Strength.	
		Tons per sq. ft.	Lbs. per sq. in.
Granite, Aberdeen Grey . .	Unwin.	1,412	22,000
,, ,, Red . .	,,	1,614	25,100
Basalt, Penmaenmawr . .	Fairbairn.	1,086	16,850
Sandstone, York Grit . .	Unwin.	712	11,050
,, Red Mansfield .	,,	609	9,560
,, Red Alton . .	,,	309	4,800
Limestone, White Italian Marble	Rennie.	1,400	21,800
Limestone, Portland . .	Unwin.	516	8,020
,, Purbeck . .	Rennie.	587	9,110
,, Ancaster . .	Royal Com.	150	2,330
,, Bramham Moor .	,,	380	5,900
Bricks, London stock, average	Unwin.	140	2,180
,, Leicester, wire cut, average . . .	,,	290	4,500
,, Staffordshire, Common Blue . . .	,,	400	6,210

CHAPTER XI

THE TESTING OF TIMBER

Tension Tests.—Considerable difficulty is encountered in the testing of timber in tension owing to the tendency of the material to crush in the grips or to shear. The portion of the specimen which enters the grips should be large in proportion to the breaking section, and should be extended for some distance out of the grips before being gradually reduced. If it is difficult to develop the full tensile strength of timber in a testing machine, it is still more difficult to do so in structures built of this material; failure invariably taking place by shearing or splitting at both connections. For this reason tension tests in timber can have little more than academic interest except in a few isolated cases. Timber is furthermore extremely variable in its properties, and, like all other materials, it is of vital importance in cases of important structures that strength calculations should be based on tests specially carried out on actual samples of the material employed. The amount of moisture, for instance, will greatly affect the results. In the adjoining tables, however, we give some standard results which will indicate what may be expected in testing.

Compression Tests.—Unlike metallic materials, the full compressive strength is frequently developed in timber struts, and the true crushing load becomes of importance. Tests are generally carried out on cubes or short cylinders, which should be as large as the testing machine employed will conveniently take. It is sometimes useful to embed the ends on a sheet of millboard, especially if the ends are rough.

Shear and Cross-bending Tests.—Timber is in the majority of cases only stressed to its full capacity when employed as

beams, and hence the most important tests are those in which the material is tested in the same manner. Whenever possible full-size beams should be employed and tested in a similar manner to iron girders, except that the ordinary knife-edges should be prevented from penetrating the fibres by placing a piece of iron plate between the knife-edge and the wood.

If the depth is at all great compared with the length, failure will invariably take place by shear along the length of the beam, and hence the shear strength becomes of considerable importance. Shear strength can be deduced either from beam tests carried out so as to cause the material to fail in this manner, or by direct experiment. In all practical structures shear failure will take place along the fibres, the strength across the grain being much more than along the grain.

With a beam supported at the ends and loaded centrally, the maximum bending moment is

$$\frac{WL}{4},$$

"W" being the central load and "L" the span.

But bending moment $M = SZ$, where S = stress in the outermost fibres, and Z = modulus of the section.

With wood, however, it is usual to introduce a constant into this equation:

$$\therefore\ M=KSZ,$$

$$\text{but } M=\frac{WL}{4},$$

$$\therefore\ \frac{WL}{4}=KSZ.$$

$$\text{And "Z" for a rectangular beam}=\frac{bd^2}{6}$$

where b=width of beam,
and d=depth of beam.

$$\therefore\ \frac{WL}{4}=K\frac{Sbd^2}{6}.$$

For samples of the same wood "S" should be approximately constant.

Then uniting all the constants

$$WL = Kbd^2.$$

$$\text{Then } K = \frac{WL}{bd^2}.$$

This expression should remain fairly constant for samples of the same wood, and consequently is often used commercially as a standard of comparison.

TABLE XXVIII.—TESTS OF TIMBER IN TENSION AND COMPRESSION, BY MR. T. LASLETT.

Carried out on tension specimens 2 inches square, 30 inches long, and compression specimens about 1, 2, 3 and 4 inch cube; crushed in direction of fibre.

Kind of Timber.	Sp. Grav.	Ult. Resist. in lbs. per sq. in. (Tension.)	Ult. Resist. in lbs. per sq. in. (Compression.)
English Oak (unseasoned)	0·858	3,837	4,900
,, ,, (seasoned)	0·893	7,571	7,480
French Oak	0·976	8,102	7,950
Dantzic Oak	0·838	4,217	7,480
American White Oak	0·969	7,021	6,070
American Oak (Baltimore)	0·762	3,832	5,890
African Oak (Teak)	0·971	7,052	—
Teak, Moulmein	0·777	3,301	5,730
Iron Wood, Burmah	1·176	9,656	11,670
Chow, Borneo	1·134	7,199	12,590
Greenheart, Guian	1·141	8,820	14,420
Sabien, Cuba	0·917	5,558	8,470
Mahogany, Spanish	0·765	3,791	6,400
,, Honduras	0·659	2,998	6,380
,, Mexican	0·655	3,427	5,600
Eucalyptus, Australian	—	—	—
Tewart	1·169	10,284	9,350
Mahogany	0·996	2,940	7,170
Iron-bark	1·150	8,377	10,300
Blue Gum	1·049	6,048	6,900
Ash, English	0·750	3,780	6,970
Ash, Canadian	0·588	5,495	5,490
Beech	0·705	4,853	—
Elm, English	0·642	5,460	5,780
Rock Elm, Canadian	0·748	9,182	8,580

TABLE XXVIII.—*Continued.*

Kind of Timber.	Sp. Grav.	Ult. Resist. in lbs. per sq. in. (Tension.)	Ult. Resist. in. lbs. per sq. in. (Compression.)
Hornbeam, England . .	0·819	6,405	8,310
Fir, Dantzic	0·603	3,231	6,940
,, Riga	0·553	4,051	5,240
,, Spruce, Canadian . .	0·484	3,934	4,850
Larch, Russia	0·649	4,203	5,820
Cedar, Cuba	0·469	2,870	4,480
Red Pine, Canada . . .	0·553	2,705	5,690
Yellow Pine, Canada . .	0·551	2,759	4,210
Pitch Pine, American . .	0·659	4,666	6,470
Kauri Pipe, New Zealand .	0·544	4,040	6,430
Hatfield's experiments.*			
Georgia Pine, American . .	—	16,000	—
Locust, American . . .	—	24,800	—
White Oak, American . .	—	19,500	—
Spruce, American . . .	—	19,500	—
White Pine, American . .	—	12,000	—
Hemlock.	—	8,700	—

* These experiments were carried out on specimens only 0·35 inch round, such a size being far too small.

TABLE XXIX.—LAWSA'S TESTS OF AMERICAN TIMBERS, 12 FEET AND 2 FEET LONG; FAILURE BY DIRECT CRUSHING.

Name of Timber.	Sectional Area in sq. in.	Ult. Strength in lbs. per sq. in.	Coeff. of Elasticity, lbs. per sq. in.
Yellow Pine . . .	42 to 102	4,544	1,996,351
White Oak . . .	32 to 93	3,470	1,398,908
Old and seasoned White Oak	28 to 87	3,957	1,817,539

TABLE XXX.—KIRKALDY'S EXPERIMENTS ON BEAMS.

Description of Timber.	Breadth and Depth in inches.	Span in feet.	Modulus of Rupture in lbs. per sq. in.	Modulus of Elasticity, lbs. per sq. in.
Pitch Pine .	from 11·18×11·30 to 13·10×13·10	12	7,626	—
Dantzic Fir .	from 10·00×12·00 to 13·25×14·38	from 8 to 12	4,581	—
,, ,, .	from 2·50×10·10 to 3·00×10·10	10	3,726	571,760
Baltic Oak. .	6·4×16·00	10	7,686	—
Baltic Red. .	from 11·72×11·82 to 11·77×11·86	12	4,890	—
English Oak .	from 4·55×12·00 to 4·58×12·00	10	9,762	—
St. Petersburg .	3·09×11·07 3·08×11·02	13	8,187	2,446,000
St. Petersburg 1st Yellow .	from 2·75× 8·75 to 3·00× 8·75	10	8,556	1,677,500
St. Petersburg 2nd Yellow .	from 2·87× 8·75 to 2·99× 8·75	10	6,918	1,396,700
Archangel. .	from 3·00×11·06 to 3·09×11·02	13	6,738	2,014,300
Archangel Deal 2A . . .	3·00×3·00	10	6,252	2,043,000
Swedish . .	from 3·08×11·07 to 4·10× 9·10	10 to 13	5,663	1,838,300
Swedish SS .	from 3·00× 9·10 to 3·15× 9·10	10	6,258	1,149,600
Swedish DDD .	from 2·93× 8·75 to 2·95× 8·75	10	6,978	1,528,700

The Modulus of Elasticity is generally deduced from beam tests, but in employing figures thus obtained it should be remembered that time has considerable effect on the elastic properties of timber, and tests extended over long periods have shown that, roughly speaking, the permanent deflection attained after six months or more may be taken as at least twice the value obtained on tests of short duration.

Tables XXIX. and XXX., taken from different sources, give results obtained by the above methods.

TABLE XXXI.—SHEAR STRENGTH OF TIMBER.

Kind of Timber.	Shearing Strength, lbs. per sq. in.		Authority.
	Maximum.	Minimum.	
Ash	700	458	Watertown Arsenal tests
Yellow Birch	815	563	
White Maple	647	367	,,
Red Oak	999	726	,,
White Oak	966	752	,,
White Pine	366	267	,,
Yellow Pine	415	286	,,
Spruce	374	253	,,
Whitewood	406	382	,,
Red Fir A	517	146	Hatt.*
,, ,, B	273	173	,,
,, ,, C	395	74	,,
Longleaf Pine (Georgia)	291	247	,,

* These results were obtained as the resistance to splitting due to longitudinal shear under cross bending.

Ligno-Concrete.—The author made some rough tests[1] on concrete reinforced with wood. Interesting results will be obtained if hard and soft woods are used. Comparisons may also be made with concrete reinforced with steel. Further tests may be devised by varying the shape of a wooden framework round which is placed the concrete.

SOME TESTS MADE ON BORNEO TIMBERS.

In 1918 Professor A. G. Warren and the author made a long series of tests on the properties of certain woods kindly supplied by Mr. Matthews, Conservator of Forests to the Government of British North Borneo. These tests were made in the University of Hongkong, and they included bending, compression, and dryness tests. The weight per cubic foot was determined.

Ten different kinds of timber were tested. The coefficient of bending strength (f) as in tests made by Professor Unwin,

[1] *Engineering*, 1910.

F.R.S., was deduced from the equation for "third point loading," which is :—$f = wl/bd^2$.

The highest figure recorded on any one specimen was for Billian and was 9·04 tons per square inch. The lowest figure for Billian was 5·34 tons per square inch, but the average of six tests was 7·29 tons. This lowest figure for Billian seems unfortunate, as all of the other specimens gave much better results.

Selangan Batu gave more uniform results in the bending tests. The highest recorded was 8·96 tons per square inch; the lowest was 6·99 tons per square inch, and the average of six tests was 8·06 per square inch.

The lowest figure recorded in the tests was for Red Serayah and it was 3·09 tons. The best result out of six tests on specimens of this wood was 4·31 tons per square inch, and the mean average was 3·54 tons.

It is considered that the most satisfactory figures for comparative purposes are those giving an average on six specimens, and the woods are therefore listed as follows :—

Name of Wood.	Mean average coefficient of Bending Strength. (Six specimens.)
Selangan Batu	8·06
Billian	7·29
Mirabow	6·77
Greeting	4·92
Camphor	4·93
Oba Sulu	4·92
Orat Mata	4·57
Kruen	4·45
Kacha	4·24
Red Serayah	3·54

From these tests it will be seen that Selangan Batu and Billian can be considered as at least twice as strong as Red Serayah. The chief demand in commercial circles appears to be for Red Serayah and Billian.

It is a very lengthy process making all of the necessary adjustments, readings and calculations to obtain this figure,

but it seems to be the most useful one for comparing the practical value of timbers used in structural work.

All of these specimens failed by bending and not by shear. The shear stress at fracture was much less than the specimen would probably withstand at shear fracture.

It is of interest to compare the above figures with these obtained by Professor W. C. Unwin on several timbers sent from various colonies to London.

Of 112 timbers tested by him only twelve gave for the "coefficient of bending" a figure above 8 tons per square inch, the highest being 9·52 tons per square inch for Red Milkwood from Natal. The next best is 9·42 tons per square inch for Mora wood, British Guinea; but the three Tasmanian woods gave results of 5·45, 4·72 and 4·06 tons per square inch; seven woods from Queensland gave results varying from 7·57 tons to 5·48 tons. None of the many Jamaica woods were as high as the average figures obtained in Hongkong for Billian and Selangan Batu.

Moisture.—In some of the timbers the moisture content varied a great deal. Thus in six specimens of camphor the highest figure obtained was 43·3 and the lowest 19·32 per cent. In Kacha the variation in six specimens was from 19·5 per cent. to 15·5 per cent. With Oba Sulu the moisture content was most regular—about 22 per cent.

In order to obtain the figure for moisture drillings were taken from the specimens used in the bending tests. These were placed in a drying oven until there was no difference in weight in the sample greater than 0·5 per cent. in 24 hours. The percentage of moisture was calculated on the weight of the dry wood.

Compression Tests.—These were on six samples of timber supplied more recently (November, 1918). The specimens were rectangular and the area under compression was $3'' \times 3''$, and the length $9''$, except in the case of the Billian the dimensions were reduced to $2'' \times 2'' \times 6''$, and Selangan Batu and Mirabow to $2\frac{1}{2}'' \times 2\frac{1}{2}'' \times 7\frac{1}{2}''$, the timber being stronger in compression than was at first thought probable.

The average crushing strength in tons per square inch on six specimens of each wood is given below:—

COMPRESSION TESTS ON SAMPLES SUBMITTED BY THE CHINA BORNEO CO.

Name of Wood.	Crushing Strength, average of 6 specimens, tons per square inch.	Highest Figure of 6 specimens, tons per square inch.	Lowest Figure of 6 specimens, tons per square inch.
Billian . .	4·99	5·59	4·45
Selangan Batu .	3·89	4·06	3·71
Mirabow . .	3·57	3·72	3·40
C. T. . . .	2·59	3·70	2·21
Camphor . .	2·47	2·65	1·99
Oba Sulu . .	2·41	2·64	2·20
W. S. . . .	2·28	2·54	1·94
Kruen . .	2·17	2·79	1·38
S. K. . . .	1·95	2·14	1·82

Tests for Uniformity.—A difficulty in testing timber is to be sure that the specimens are fair representatives. It is known that different results are obtained from the same wood if the moisture content varies. But about 70 specimens of Billian and Selangan Batu were taken from a stack of timber felled at the same time, and each of the specimens had about the same life history.

The ordinary compression test was applied, the load being increased at the rate of about 15 tons per minute.

For Billian the mean value of the crushing strength on 72 specimens was 4·68 tons per square inch.

It was found that 32 specimens gave results which were within 5 per cent. of the mean crushing strength; 46 specimens gave results which were within 7½ per cent. of the mean; 51 specimens gave results which were within 10 per cent. of the mean; 60 specimens gave results within 12½ per cent. of the mean.

The greatest variation for Billian was 0·82 ton per square inch above and 0·98 ton per square inch below the mean value.

Seventy specimens of Selangan Batu were tested. The

mean crushing strength was found to be 3·76 tons per square inch. Of the 70 specimens 47 were within 5 per cent. of the mean crushing strength; 56 were within 7½ per cent.; 62 were within 10 per cent., and 65 within 12½ per cent.

The greatest variation was 0·5 ton per square inch above and 0·36 ton per square inch below the mean value.

There is a growing demand in China for woods for structural purposes, and when the valuable physical properties of these Borneo timbers are realised by engineers there will be a great increase in their consumption.

These tests show that the Borneo timber is very useful for commercial purposes.

CHAPTER XII

EXPERIMENTS IN COLLEGE LABORATORIES

One of the regular parts of every engineering student's course of study is the carrying out of tests in a materials testing laboratory, and the following is suggested as a suitable and systematic series of experiments. It is assumed that the student has already completed a first-year's course in applied mechanics, and is familiar with the use of verniers, micrometers, microscopes, etc. Few students will have the opportunity to carry out all of the tests mentioned, and much must, of course, depend on the resources of the particular laboratory in which the student is working. It is not even suggested that the experiments should be carried out strictly in the order given, although an attempt has been made to arrange them as far as possible in the usual order in which they should be performed. The general instructions to the student should be carefully read and, subject to the discretion of the particular professor under whom the student is working, adhered to faithfully. It is hoped that the tables prepared for "setting" these experiments will be found useful by both students and demonstrators. They are intended to show at a glance the work which has already been done by the student, and suggesting fresh experiments to be performed.

General Instructions to Student.

Note-Books.—Each student should be provided with a note-book for entering records of all laboratory tests and illustrative sketches. In any case this book should have good paper and be provided with stiff binding. The following method has been found excellent for students preparing for a degree in engineering.

All notes and descriptions should be on separate sheets of thick foolscap; curves on foolscap size sheets of squared paper; diagrams on drawing paper and photographs pasted on same. All these can be bound up at the end of the session at quite a small cost. Needless to say, blank pages should be left for further additions. Such a book, even apart from examinations, is an excellent record of a student's work and neatness, suitable for showing to a prospective employer. In all cases a good wide margin should be left at the side of the page; when separate sheets are used an allowance for binding is necessary. On no account should different subjects (such as heat engines and materials) be mixed in the same note-book.

Before starting an experiment the student should make a sketch of the apparatus to be used, employing diagrammatic sketches rather than scale drawings. He should then calculate approximate data so as to know what to expect during the experiment. Thus in the case of the determination of Young's modulus he should measure the specimen, and look up in the tables the stress at the elastic limit of the material. He will then be able to form an estimate of the load which the specimen can safely withstand without damaging the instrument. This must be well within the calculated elastic limit of the material.

In marking out specimens centrepops should be light, as in testing to destruction it is possible that they may have a considerable effect on the ultimate strength.

The greatest care should be taken with instruments and apparatus of all kinds. Instruments of precision, such as extensometers, cannot be handled too carefully.

Before testing the student should enter in his rough book the date, and as far as possible every dimension which can possibly affect the result. Nothing is more annoying than to find, after a long and careful experiment lasting over, perhaps, two or three days, that some vital dimension was not taken at the beginning, and as a consequence the whole test spoiled. During the test every reading should be entered in the rough

book directly it has been taken; never trust the memory more than a few minutes when carrying out scientific work.

As soon after the finish of the test as is possible a full report of the experiment and apparatus used should be written up in the recording note-book stating: (*a*) object of test; (*b*) apparatus employed, including details, with sketches, if necessary, of such parts as grips, shape of specimen, etc.; (*c*) order of making observations; (*d*) record of observations; (*e*) deduced results showing carefully how such were obtained; (*f*) graphical representation of results when possible; (*g*) comparison with standard laws or results to be verified.

Wherever possible, photographs of apparatus, specimens, fractures, etc., should be pasted into the note-book.

In describing experiments it cannot be too strongly impressed that language is "the first tool of the mind." Great care should be taken by the student in expressing clearly and in suitable words any work upon which he has to write a report. Inaccuracy of expression is as great a source of error as inaccuracy of observation. Huxley's theory of style was "to say that which has to be said in such language that you can stand cross-examination on each word."

Experiments Suitable for College Laboratories.

On Wires and Springs.

1. **To Determine the Relation between Load and Extension of a Spring.**—The apparatus is usually found set up, and consists simply of a spring attached to a hook at the top and provided with a scale pan or similar contrivance at the bottom. A vernier moving over a scale gives the deflection. Load with increasing weights so as to get ten or more readings, and plot a curve showing the above relation. It should come out a perfectly straight line. Deduce the "slope" of same and note.

2. **To Determine Relation between Load and Compression of a Spring.**—This is carried out in an exactly similar manner to experiment 1, and similar results deduced.

3. **Extension of a Short Wire to Determine Young's Modulus.**—See page 165 for general description. Care should

be taken not to overload the wire. Take as many readings as possible, plot curve as in experiment 1, deduce Young's modulus from slope of curve and the dimensions of the wire. This experiment may be repeated for wires of different material.

4. **Extension of a Long Wire.**—Some laboratories are provided with a very long wire (say 90 feet or more) running on pulleys down the laboratory. Readings as in experiment 3, but only scale and vernier necessary for extension. Take readings with increasing load and decreasing load; plot curves for both sets of readings. The curves will not coincide owing to friction of pulleys, hence take mean of the two sets and deduce value of as before.

5. **Wire Stressed to Fracture on Autographic Apparatus.**—(See description of this experiment on p. 166.) It is not desirable to ink in autographic diagrams if they are drawn by a pencil apparatus, but, if faint, it is allowable to dot with a sharp pencil or a pen along the line traced out. Copies may be taken with tracing paper.

6.[1] **Value of C by Torsional Deflection of a Wire.**—(See p. 135.) Take increasing and decreasing loads as before and obtain mean value to eliminate friction. Value of C deduced from the formula

$$C=\frac{584\ Ml}{\theta D^4},$$

where M is twisting moment in lbs. inches, l the length in inches, D the diameter of wire in inches, and θ the twist in degrees. Obtain the mean value of $\frac{M}{\theta}$ by plotting a curve showing relation between them. This should come out to a straight line.

7.[1] **Value of C by Torsional Vibrations of a Wire.**—(See p. 136.)

$$\text{Value of C deduced from } C=\frac{128\pi e}{gd^4}\left[\frac{(m_1-m_2)x^2}{t_1^2-t_2^2}\right]$$

where m_1, m_2, x, etc., have the values given on p. 136.

[1] If same kind of wire is employed for experiments 3, 6, and 7, the value of Poisson's ratio should be deduced from formula $E=\frac{(2\,C\,m+1)}{n}$ where $\frac{1}{n}$ is Poisson's ratio.

8. Spring Tested in Extension for Value of C, and

9. Spring Tested in Compression for Value of C.—These experiments can be carried out in a similar manner to experiments 1 and 2, but for large springs either a special apparatus is employed, or in the case of 9 this can be performed in an ordinary testing machine arranged for compression. Deflection can be taken in the latter case by measuring with an internal micrometer between the compression plates.

$$\text{C is obtained from the formula } C = \frac{2{\cdot}55\ D^2LW}{\delta\ d^4},$$

where D is mean diameter of coils, L total length of spring if pulled out to a plain rod (approx. $n\pi D$), d is diameter of wire, and $\frac{W}{\delta}$ relation between load and deflection —obtained by plotting a curve.

EXPERIMENTS WITH TESTING MACHINES (TENSION).

10. Testing Small Specimen for Yield Point and Fracture in a Small Testing Machine.—Some such machine as the Bailey machine can be employed (see p. 121). As many materials as the student has time and opportunity to test should be employed; in any case (*a*),[1] (*c*), and (*e*).

11. Calculating Mechanical Advantage of a Large Testing Machine and Checking for Sensitiveness and Accuracy.—See p. 47 for such a test fully worked out.

12. Yield Point of Full Size Specimen by drop of beam. This will also give experience in working a machine and setting up specimens (see p. 85). Materials suggested, (*a*), (*b*), (*e*), and (*g*).

13. Fracture of Various Materials.—This involves the marking out of specimens, setting up, determination of yield point and measurement of elongation per cent., reduction of area, etc. (see pp. 86, 87, and 89). Materials suggested, (*a*), (*b*), (*c*), (*d*), (*e*), (*f*), (*g*), and (*h*).

14. Full Commercial Test.—Test, say, half a dozen

[1] These letters refer to mild steel (*a*), wrought iron (*b*), cast iron (*c*). copper (*d*), brass (*e*), gun metal (*f*), aluminium (rolled) (*g*), tool steel (*h*).

specimens of the same material as in experiment 13, carefully noting kind of fracture, etc.; compare with a standard specification (see Appendix II.), draw up a full report on the material (see pp. 5 and 85).

15. **Test to Fracture with Autographic Diagram.**—This will depend on the machine at disposal of student. See pp. 72 to 82 for description of various methods. The yield point, maximum load, and breaking load should as far as possible be read independent of the autographic apparatus and noted. Mark all particulars of test on the autographic diagram itself, together with yield stress, etc.

16. **Determination of Young's Modulus** with medium and full-size specimens. See Chap. IV. for various types of strain-measuring instruments. Preliminary experiments should be made on a small machine such as that made by the Cambridge Scientific Instrument Making Company. Great care should be taken in testing cast materials that the breaking load is not approached, as the fracture of the specimen with some types of extensometer is disastrous.

17. **Determination of Elastic Limit by Extensometer.**—Increase the load by small and uniform amounts, calculating after each reading the increase in length. The passing of the elastic limit will be observed by an increase in the extension per unit load. Materials suggested, (*a*), (*b*), (*d*), and (*g*). If (*a*) is a good specimen, the elastic limit will practically coincide with the yield point.

18. **Time Effect on Hardening.**—Fit specimen with extensometer, take load up just beyond first appearance of yield, and keep load constant until no further slipping. Slightly increase load, and note time and extension until slipping again ceases. Repeat with further loads until complete breakdown. Plot stress-strain curve and mark on times. See p. 104.

19. **Artificial Raising of Elastic Limit by Overstraining.**—Take extensions up to beyond yield point, remove load and repeat taking load somewhat higher than previously. Repeat this several times until complete breakdown, and plot series of curves so as to show comparison. See p. 102, etc.

20. **Effect of Boiling Water on Overstrain.**—Repeat experiment 19, but after each loading boil specimen at 100° C. for ten minutes. Plot curves as before. Try also allowing the specimen to stand for one or more days. See p. 104.

21. **Annealing Tests.**—Run a series of tests on specimens of (*a*), (*d*), and (*h*), trying the effect of annealing in an oven at various temperatures. See pp. 104 and Appendix IV.

22. **Effect of Notches.**—Run a series of breakdown tests on specimens which have been slightly notched with a triangular file to varying depths. Try also effect of sudden changes of cross-section by machining pieces out of the sides of flat specimens.

Compression Tests.

23. **Compression of Short Specimens** (ductile).—Short specimens can be tested for yield point (when this is well marked), and complete breakdown as with tension tests. See p. 89.

24. **Compression of Short Specimens** (brittle).—Cast iron is the usual material employed. Care should be taken that, when fracture takes place, the broken pieces cannot fly out and injure anybody. It is a good practice to place a piece of sacking so as to prevent this kind of accident. See p. 93.

25. **Effecting of Bedding.**—Repeat 23 and 24, using pieces of soft lead or copper between the specimen and compression plates, and compare results.

26. **Testing of Struts.**—(See p. 47.) (*a*) Free ends. Run a series with varying length and constant diameter, using a ball so as to secure that ends are quite free. Plot relation between buckling load and length, and try checking Gordon's or Rankine's formulæ. (*b*) Fixed ends. Take two cast-iron blocks in which a hole has been drilled the same diameter as the specimen. Cut off a number of lengths from a mild-steel bar and drive into the blocks. Plot as in (*a*) ; $\frac{5}{8}''$ is a suitable diameter for both (*a*) and (*b*). (*c*) Hollow struts. Run a series of tests with drawn tubes. Mild steel or brass are suitable materials.

27. Alternate Tension and Compression.—Try some of the experiments 18, 19, 20, and 21 in alternate tension and compression. Find if there is an elastic range, *i.e.*, whether raising the yield point in tension lowers it in compression.

Bending Tests.

28. Testing of Beams (deflection).—These can be carried out on the machine described on p. 39, or on a universal testing machine set up for beam testing. As far as possible test beams and cantilevers in deflection with various methods of fixing, supported at both ends, fixed at both ends, etc., and compare results with the standard formula. Obtain Young's modulus.

29. Breaking of Beams.—Test various lengths of cast-iron beams for fracture. Where facilities are provided, full-size girders, both plain and built up, can be tested in the same manner.

30. Obtaining Elastic Curve.—This is carried out on an apparatus similar to that described on p. 41. Compare results with those obtained by formula.

Torsion Tests.

31. Obtaining C.—Some such machine as is described on p. 119 can be employed, using a torsional deflectometer as on p. 154. The value of C is calculated as in experiment 6.

32. Fracture of Torsion Specimens.—This can be carried out either on a special machine or on a universal testing machine provided with torsion attachment. See pp. 119 and 121. Specimens both solid and hollow should be tested. When possible, observe whether any change takes place in length of specimen.

33. Effect of Flaws and Surface Markings.—Try the effect of slightly cutting notches with a lathe tool into the surface of a torsional specimen.

Miscellaneous Tests.

34. Impact Tests on Plain and Notched Specimens.—See pp. 137 to 149 for various machines and methods.

35. **Shear Tests,** double and single.—See p. 155 for description of shear shackles, etc., and method employed.

36. **Punching Tests.**—See p. 159.

37. **Cold Bending Tests.**—Try several specimens, and compare with specification on p. 234.

38. **Hammering Tests.**—Test samples as forged, cold-drawn and annealed specimens of copper, and compare with clauses 1 and 2, Appendix II., p. 234.

39. **Rough Examination of Microstructure.**—See p. 9.

40. **Repeat Stresses.**—This requires special apparatus, and depends on the facilities of the laboratory. Sankey's band-bending machine (see p. 181) is a useful instrument for a laboratory not otherwise provided.

41. **Combined Bending and Torsion.**—Many instructive experiments can be carried out in this direction by methods which will readily suggest themselves. Results on cast-iron test pieces are given on p. 251.

42. **Combined Torsion and Direct Stresses.**—See p. 236 and Bibliography. Much research work still remains to be done on this subject. Original papers of previous experimenters should be consulted before fresh work is started.

43. **Tests of Balls.**—A series of experiments should be carried out on increasing sizes of balls (either cast steel or gun metal), according to some such method as is described on p. 161. Curves should be drawn showing relation between fracture load and diameter.

44. **Hardness Tests.**—These can be performed by any of the methods described on pp. 145 to 154. Whichever method is employed, it is advisable to run a comparative test on such standard materials as soft annealed Swedish iron or soft annealed electrolytic pure copper. Hardness can only be expressed by comparison, and consequently this should be clearly brought out in the results.

45. **Find Relation Between Hardness Number and Tensile Strength.**—Use range of materials closely allied, such as steels with varying percentage of carbon, and see if a constant law can be obtained. See p. 151.

46. **Testing Thick Cylinder.**—Test a brittle material. The specimen to be turned inside and out and fitted with an accurately turned plunger; partially fill the inside hole with paraffin wax, and load with compression machine.

Testing of Timber.

Consult Chapter V. for various methods and probable results.

47. **Timber Tests in Tension.**—Carry out by method described on p. 207, using as many specimens and as many different varieties of timber as possible.

48. **Crushing Timber.**—See p. 207.

49. **Shearing Tests on Short Beams.**—See p. 208.

50. **Testing of Long Timber Beams.**—Test for deflection, and, as far as possible, look for increase of deflection with time.

51. **Testing Long Timber Struts.**—Run a series of varying lengths, and check with standard formula.

Testing of Cements and Concrete.

Consult Chapter V., and, as far as possible, adhere to the methods suggested there. The following tests will be found described on pp. 189 to 204.

52. **Specific Gravity Test.**—Special specific gravity bottles are made for this work, but ordinary apparatus and methods can, of course, be employed. Use petroleum as displacement liquid.

53. **Setting Test.**—Try various cements and different proportions in concrete, also try varying percentage of water.

54. **Tensile Tests.**—Prepare standard briquettes according to method described on p. 190, and compare results with minimum specification.

55. **Compressive Tests.**—See p. 194.

56. **Soundness Test.**—Use the Le Chatellier method, as described on p. 192.

57. **Compressive Tests on Stones.**—See pp. 194 and 206.

TABLE XXXII.—RECORD OF LABORATORY EXPERIMENTS.

Experiments carried out by ______________

Experiment No.	Description of Experiment.	Set by.	Date.	Examined by.	Date.
1	Relation between load and extension of spring . . .				
2	Relation between load and compression				
3	Determination of E on short wire				
4	Determination of E on long wire				
5	Test of wire on autographic apparatus				
6	Value of C by torsional deflection of wire				
7	Value of C by oscillation method				
8	,, ,, by spring in tension				
9	,, ,, in compression .				
10	Determination of yield point on small machine . . .				
11	Checking of large testing machine				
12	Yield point on large machine .				
13	Fracture of various materials .				
14	Complete commercial test and report				
15	Test to fracture with autographic diagram . . .				

TABLE XXXII.—*Continued.*

Experiment No.	Description of Experiment.	Set by.	Date.	Examined by.	Date.
16	Determination of Young's modulus with extensometer				
17	Elastic limit by extensometer .				
18	Hardening effect of time, etc. .				
19	Artificial raising of elastic limit				
20	Effect of low temperature annealing				
21	Effect of high temperature annealing				
22	Effect of notching tension specimen				
23	Ductile specimens in compression				
24	Brittle specimens in compression				
25	Effect of bedding specimens .				
26	Tests on struts, (*a*), (*b*), and (*c*)				
27	Alternate tension and compression				
28	Deflection of beams. . .				
29	Breaking of beams . . .				
30	Elastic curve of beams . .				
31	Determination of C (torsion test)				

TABLE XXXII.—*Continued.*

Experiment No.	Description of Experiment.	Set by.	Date.	Examined by.	Date.
32	Fracture of torsion specimen .				
33	Effect of flaws and surface markings (torsion) . .				
34	Impact tests				
35	Shear tests				
36	Punching tests . . .				
37	Cold bending tests . . .				
38	Hammering tests . . .				
39	Rough microstructure examination				
40	Repeat stresses . . .				
41	Combined bending and torsion				
42	Combined torsion and direct stresses				
43	Tests on balls				
44	Hardness tests				
45	Comparison of tensile strength and hardness				
46	Testing thick cylinder . .				
47	Timber test in tension . .				

TABLE XXXII.—*Continued.*

Experiment No.	Description of Experiment.	Set by.	Date.	Examined by.	Date.
48	Timber test-crushing test .				
49	Shear test on short beams .				
50	Testing of long timber beams .				
51	Testing of long timber struts .				
52	Specific gravity of cement .				
53	Time of setting test . , .				
54	Tensile tests with cements, etc.				
55	Compression tests ,, ,,				
56	Soundness tests of cements .				
57	Compressive tests on stones .				
58	Tests on ferro-concrete beams .				
59	Tests on wood-concrete beams .				

APPENDIX I.

STANDARD RESULTS OF TESTS ON THE STRENGTH OF MATERIALS.

THE following tables, taken from various sources, give the results obtained on various materials and will indicate the kind of results to be expected in practice. It will be found on comparison of results from different sources that there are often wide differences; from which it will be seen that in all important machines and structures, where the material is to be used in the most economical manner, it is essential that samples and specimens of the *actual* material employed should be tested and under as near the conditions of use as is possible in the testing laboratory.

TESTS IN TENSION, TORSION, AND SHEAR ON THE CHIEF MATERIALS OF CONSTRUCTION.[1]

TABLE XXXIII.—TENSION.

Material.	Specimen.	Elastic Limit. Lbs. per sq. in.	Breaking Stress. Lbs. per sq. in.
Wrought iron, Netherton Crown best.	1 2	31,970 35,550	47,950 48,850
Bessemer steel.	1 2	69,760 70,700	116,930 108,550
Crucible steel.	1 2	67,500 71,680	113,020 120,680
Rivet steel.	1 2	40,000 40,190	65,500 62,630
Crown rivet iron.	1 2	37,500 37,970	56,700 55,300
Cast iron, skin on.	1 2 3	— — —	28,310 22,140 26,380
Cast steel (cut from casting).	1 2	38,350 38,870	85,700 84,850

[1] Proc. Inst. Civ. Eng., vol. xc., pp. 396–407.

TABLE XXXIII.—TENSION—*Continued.*

Material.	Specimen.	Elastic Limit. Lbs. per sq. in.	Breaking Stress. Lbs. per sq. in.
Cast steel, *in compression.*	1 2	39,010 39,860	— —
Siemens-Martin steel.	1 2	37,060 35,760	57,500 57,900
Wrought iron, S.C. Crown.	1 2	38,260 38,490	54,330 55,690
Muntz metal bar.	1 2	25,000 25,000	57,500 56,540
Gunmetal, Cu. 64 parts, Sn. 8, Zn. 2 parts.	1 2	17,500 15,000	29,070 32,380

TABLE XXXIV.—TORSION.

Material.	Specimen.	Elastic Limit. Lbs. per sq. in.	Breaking Stress. Lbs. per sq. in.
Wrought iron, Netherton Crown best.	1 2 3	20,560 18,700 18,900	57,800 54,900 56,600
Bessemer steel.	1 2 3	46,400 45,400 44,500	101,000 99,460 99,550
Crucible steel.	1 2 3	43,100 43,600 43,300	97,900 90,000 96,800
Landore rivet steel.	1 2 3	37,200 23,200 22,400	78,700 66,840 67,100
Netherton Crown rivet iron.	1 2 3	22,950 21,600 25,200	64,700 64,700 64,600

TABLE XXXV.—TORSION—*Continued.*

Material.	Specimen.	Elastic Limit. Lbs. per sq. in.	Breaking Stress. Lbs. per sq. in.
Cast steel.	1 2 3	24,300 23,500 22,400	78,200 78,250 77,000
Siemens Martin steel.	1 2 3	24,200 21,800 21,800	65,300 63,000 60,600
Wrought iron, S.C. Crown.	1 2 3	22,950 22,100 23,700	67,400 62,700 68,400
Muntz metal.	1 2 3	19,700 19,200 19,700	59,000 57,600 59,000
Gun-metal, Cu. 64, Zn. 2, and Sn. 8 parts.	1 2 3	12,100 12,100 12,100	33,800 36,500 36,200
Cast iron ; Turned. 1 part Dalmelington, 5 parts best scrap.	Highest Lowest Mean of Six	— — —	40,100 28,450 33,040
Cast iron, skin on.	1 2 3	— — —	46,800 36,600 38,500
Cast iron ; Turned, 1 part Sunderland, 3 parts best scrap.	Highest Lowest Mean of Six	— — —	41,800 33,900 38,200
Cast iron. Skin on.	Highest Lowest Mean of Five	— — —	37,500 32,150 34,330

TABLE XXXVI.—SHEAR OR "RIVET" TESTS.

Material.	Specimen.	Shear Strength. Lbs. per sq. in.	Material.	Specimen.	Shear Strength. Lbs. per sq. in.
Wrought iron, Netherton Crown best	Highest Lowest Mean of 6	44,350 40,000 42,050	Wrought-iron, S.C. Crown	Highest Lowest Mean of 5	46,950 46,030 46,510
Bessemer steel	Highest Lowest Mean of 6	81,910 76,780 78,880	Muntz metal	Highest Lowest Mean of 6	42,860 40,270 42,000
Crucible steel	Highest Lowest Mean of 6	76,200 73,500 74,500	Gunmetal, Cu. 64, Sn. 8, Zn. 2 parts	Highest Lowest Mean of 6	30,650 22,630 27,960
Landore rivet steel	Highest Lowest Mean of 4	53,180 50,540 51,570	Cast-iron. Turned. Dalmeling-ton, 1. Best scrap 5 parts	Highest Lowest Mean of 11	13,860 10,280 11,860
Netherton Crown rivet iron	Highest Lowest Mean of 6	48,800 47,160 47,870			
Cast steel	Highest Lowest Mean of 5	63,520 58,720 60,160	C.I. Turned. Sunder-land, 1. Best scrap, 3 parts	Highest Lowest Mean of 12	13,740 9,280 11,420
Siemens-Martin steel	Highest Lowest Mean of 5	48,300 45,850 46,910	Ditto, ditto. Skin on	Highest Lowest Mean of 6	13,920 6,740 8,810

TABLE XXXVII.—PROPERTIES OF MATERIALS.

Material.	Melting Point (Fahr.).	Weight per cub. in.	Tons per sq. in.						Tons per sq. in.		Extension per cent. on 10 in.	Reduction in Area.
			Elastic Limit.			Breaking Strength.			E. Tension or Compression.	C. Shear.		
			Tension.	Compression.	Shear.	Tension.	Compression.	Shear.				
Steel, 0·1 per cent. C.		—	13—14	—	10—11	21—22	—	16—17	13,000 14,000	5,000 6,000	27—30	45—50
„ 0·2 „ „	2,400° to 3,000°	—	17—18	16—17	13—14	30—32	—	24—26	„	„	20—23	27—32
„ 0·5 „ „		·283	20—21	—	16—17	34—35	—	28—29	„	„	14—17	17—20
„ 1·0 „ „		—	28—29	22—24	21—23	50—55	—	42—47	14,000	„	4—5	7—8
Cast steel (unannealed)		—	10—11	—	—	20—25	—	—	12,000 to 12,500	—	5—12	6—13
„ „ (annealed)		—	15—17	—	—	30—40	—	—		—	10—20	15—35
Tool steel (unhardened)		·290	35—45	40—50	—	40—70	—	—	14,000 to 15,000	—	1—5	1—5
„ „ (hardened)		·290	60—80	—	—	60—80	—	—		—	Nil.	Nil.
Rivet steel		—	15—17	—	12—14	26—28	—	21—22	—	—	20—35	30—50
Steel wire (English) drawn,		·266	—	—	—	54—63	—	—	12,500	—	—	—
„ „ (common), blue		·266	—	—	—	147	—	—	11,600	—	—	—
Pianoforte wire (English)	—	·278	—	—	—	152	—	—	12,900	—	—	—
Manganese steel, cast	—	—	—	—	—	37	—	—	—	—	—	—
Nickel steel, forged (annealed)	—	(Alloys	Research	Mech.	Eng.	7th	Report.)	—	—	—	(On 2 in.)	—
0·95 Ni, 0·13 C, 0·72 Mn	—	·282	20	—	—	27	—	—	—	—	41	63
3·82 Ni, 0·19 C, 0·65 Mn	—	·281	25	—	—	33	—	—	—	—	35	55
11·39 Ni, 0·18 C, 0·93 Mn	—	·280	45	—	—	89	—	—	—	—	12	26
29·07 Ni, 0·14 C, 0·86 Mn	—	·291	16	—	—	37	—	—	—	—	48	51
Wrought-iron bars	3,000° to 3,300°	·278	12—15	—	10—12	21—24	—	17—19	11,000 to 13,000	5,000 to 6,000	10—30	15—40
Plates with grain		·278	13—15	—	—	20—22	—	—	—	—	5—10	7—12
„ across grain		·278	11—13	—	—	18—20	—	—	—	—	2—6	3—7
Cast iron	2,000—2,500°	·260	(No	marked	limit.)	7—11	35—60	8—13	6,000 to 10,000	2,500 to 4,000	Practically nil.	
Brass, yellow	1,700° to 1,850°	·283 to ·289	2—4	—	—	7—10	5—6	—	4,000 to 4,100	2,000	10—12	12—15
„ sheet			—	—	—	13—15	—	—				
„ tube			—	—	—	35—44	—	—				
„ cast			—	—	—	9	—	—				
Copper, wrought	2,000°	·328	2—4	10—13	—	14—15	20—25	11—12	7,000 to 7,500	—	35—40	50—60
„ hard-drawn	—	·328	—	—	—	26	—	—		—	2—5	40—55
Aluminium	1,300	·094	2—7	8—10	—	7—10	—	5—6	3,000—5,000	1,700	4—15	30—70
Muntz metal	—	—	20—25	—	—	25—30	—	—	—	—	10—20	30—40
Delta metal (cast)	—	—	5—8	12—14	—	14—20	60—70	—	6,000	—	8—16	10—22

TABLE XXXVIII.—STRENGTH AND ELASTICITY OF COMMERCIALLY PURE MATERIALS (MISCELLANEOUS).
(Tabulated from various reliable sources.)

Material.	E. Lbs. per sq. in.	Tension.		Compression.		Shear.	
		Elastic Limit. Lbs. per sq. in.	Ultimate Strength. Lbs. per sq. in.	Elastic Limit. Lbs. per sq. in.	Ultimate Strength. Lbs. per sq. in.	Elastic Limit. Lbs. per sq. in.	Ultimate Strength Lbs. per sq. in.
Cadmium	Drawn, 7,713,000 (W.) Annealed, 7,555,000 (W.)	Annealed, 142 (W.) * Drawn, 171 (W.) *					
Copper	*Etiré*, 17,702,000 (W.) Annealed, 14,958,000 (W.) Cast, 9,091,000 (Th.) (varies with load) C 6,237,000	11,620 (Th.) 11,000 ,, 14,400 ,,	19,872 (Th.) 12,760 ,, 27,800 ,, Wrought, 33,600 (A.) Cast, 19,000—26,100 (A.) Rolled (Mean of 66), 32,826 (F.I.) 56,810 (60° F.) (P.D.) 48,220 (500° F.) ,,	22,400 to 29,000	Cast, 48,000—36,000 (Th.)	12,590 (Th.) 11,400 (Th.)	27,800 (S.) 35,910 (Th.) 28,430 (Th.)
Glass	Mirror, 8,792,000 (W.) Crystal, 5,830,000 (W.)		Flint, 2,413 (F.) Green, 2,896 ,, Crown, 2,546 ,,		Flint (Cylindrical), 34,850—20,780 Flint (Cube), 14,240—11,820		
Gold	Drawn, 11,564,000 (W.) Annealed, 7,942,000 (W.)	Annealed, 4,266 (W.) * Drawn, 19,200 (W.) *	17,100—26,200 (B.)				
Lead	Drawn, 2,564,000 (W.) Annealed, 2,457,000 (W.)	Annealed, 284 (W.) * Drawn, 355 (W.)*	Cast, 1,824 (R.) Sheet, 1,926 ,, Pipe, 2,240 ,,				

TABLE XXXVIII.—STRENGTH AND ELASTICITY OF COMMERCIALLY PURE MATERIALS—*Continued.*

Material.	E. Lbs. per sq. in.	Tension.		Compression.		Shear.	
		Elastic Limit. Lbs. per sq. in.	Ultimate Strength. Lbs. per sq. in.	Elastic Limit. Lbs. per sq. in.	Ultimate Strength. Lbs. per sq. in.	Elastic Limit. Lbs. per sq. in.	Ultimate Strength. Lbs. per sq. in
Palladium	Drawn, 16,721,000 (W.) Annealed, 13,920,000 (W.)	Annealed, 7,110 (W.) * Drawn, 25,600 (W.) *	51,750t o 52,640 (B.)				
Platinum	Drawn, 24,237,000 (W.) Annealed, 22,067,000 (W.)	Annealed, 20,600 (W.) * Drawn, 37,000 (W.) *	32,300 to 32,700 (B.)				
Silver	Drawn, 10,463,000 (W.) Annealed, 10,155,000 (W.)	Annealed, 4,266 (W.) * Drawn, 16,350 (W.) *	40,300 to 40,550 (B.)				
Tin	Cast, 4,608,000 (T.) Cast, 1,147,000 (Th.) (varies with load)	1,670 to 2,000 (Th.)	3,500 (Th.) 2,760 ,, 5,600 (M.) 4,700 (R.)		Cast, 6,400 (Th.) 10 % shortening.	1,437 (Th.) 1,087 ,,	3,196 (Th.) 3,297 ,,
Zinc	Cast, 13,680,000 (T.) Ingot, 12,420,000 (W.) *Etiré*, 17,702,000 (W.)	4,050 (Th.)	5,400 (Th.) Cast, 8,000 (S.)		22,000 (Th.) 10 % shortening.	3,500 (Th.)	9,186 (Th.)

Authorities.—(T.) Tredgold; (W.) Wertheim; (Th.) Thurston; (B.) Bandrimont; (M.) Mallet; (R.) Rennie; (S.) Storey; (F.) Fairbairn; (Mo.) Morrin; (A.) Anderson; (F.I.) Franklin Institute; (P.D.) Portsmouth Dockyard Experiments.

* Experiments on wires. Elastic Limit taken when extension was ·0005 of original length.

APPENDIX II.

ADMIRALTY RULES FOR TESTING MATERIALS FOR MACHINERY.

1. **Steel Castings for Machinery.**—Steel castings for the machinery are to satisfy the following conditions:—Tensile strength, not less than 28 tons per sq. inch, with an extension in 2 inches of length of at least 23 per cent. Bars of the same metal, 1 inch square, should be capable of bending cold, without fracture, over a radius not greater than $1\frac{5}{8}$ inches, through an angle depending on the ultimate tensile strength, this angle to be not less than 90° at 28 tons ultimate strength, and not less than 60° at 35 tons ultimate strength and in proportion for strength between these limits. For intricate thin castings the extension in 2 inches of length is to be at least 10 per cent.; and the bending angle is to be not less than 20° at 28 tons ultimate strength, and 15° at 35 tons ultimate strength, and in proportion for strengths between these limits. Test pieces are to be taken from each casting. All steel castings are also to satisfactorily stand a falling test, the articles being dropped from a height of 12 feet (or as may be approved) on a hard macadamised road or a floor of equivalent hardness.

It is to be distinctly understood that contractions or defects in steel castings are not to be made good by patching, burning, or by electric welding, without the sanction of the Admiralty overseers.

2. **Steel Forgings for Machinery.**—All steel forgings are to satisfy the following conditions: Ultimate tensile strength, not less than 28 tons per sq. inch, with an extension in 2 inches of length of at least 30 per cent. Bars of the same metal, 1 inch square, should be capable of being bent cold, without fracture, through an angle of 180° over a radius not greater than $\frac{1}{4}$ inch. Test pieces are to be taken from each forging. Crank and propeller shafts are to have test pieces taken from each end, and the ultimate tensile strength of the material of these shafts must not exceed 32 tons per square inch.

For all important forgings, such as crank and propeller shafts, connecting and piston rods, the forgings are to be gradually and uniformly forged from solid ingots, from which at least 30 per cent. of the top end of the ingot has been removed before forging, and at least 3 per cent. of the total weight of the ingot from the bottom end after forging. The sectional area of the body of the finished forging is to be not more than $\frac{1}{6}$ the original sectional area of the ingot.

3. **Cast Iron.**—Test pieces to be taken from such castings as may be considered necessary by the inspecting officer. The minimum tensile strength to be 9 tons per sq. inch, taken on a length of not less than 2 inches. The transverse breaking load for a bar 1 inch square, loaded at the middle between supports 1 foot apart, is not to be less than 2,000 lbs.

4. **Gun-metal, Naval Brass, and White Metal.**—The gun-metal used for all castings throughout the whole of the work supplied by the contractors is, unless otherwise specified, to contain not less than 8 per cent. of tin, and not more than 5 per cent. of zinc, the remainder to be of approved quality copper; the exact proportion of tin above 8 per cent. being arranged as may be required, depending on the use for which the gun-metal is intended. The ultimate tensile strength of gun-metal is to be not less than 14 tons per sq. inch, with an extension in 2 inches of length of at least 7½ per cent. The composition of any naval brass used is to be: Copper, 62 per cent.; zinc, 37 per cent.; and tin, 1 per cent. All naval brass bars are to be cleaned and straightened. They are to be capable of (1) being hammered hot to a fine point, (2) being bent cold through an angle of 75° over a radius equal to the diameter or thickness of the bars. The ultimate strength of naval brass bars ¾ inch diameter and under is not to be less than 26 tons per sq. inch, and for round bars above ¾ inch diameter, and square bars not less than 22 tons per sq. inch, whether turned down in the middle or not. The extension in 2 or 4 inches of length is to be at least 10 per cent. Breaks within ½ inch of the grip are not to count. Cuttings from the propellers and other important gun-metal castings and naval brass work will be sent to Portsmouth Dockyard for analysis. The white metal used for bearing surface is to contain at least 85 per cent. of tin, not less than 8 per cent. of antimony, and about 5 per cent. of copper; zinc or lead should not be used. The brasses are to be carefully tinned before filling with white metal.

5. **Copper for Pipes.**—Strips cut from the steam and other pipes, either longitudinally or transversely, are to have an ultimate tensile strength of not less than 13 tons per sq. inch when annealed in water, with an elongation in a length of 2 inches or 4 inches of not less than 35 and 30 per cent. respectively. Such strips are also to stand bending through 180° cold until the two sides meet, and of hammering to a fine edge without cracking.

APPENDIX III.

RESEARCHES ON COMBINED STRESS.[1]

In engineering design it frequently happens that the material is simultaneously subjected to more than one single stress, and in this case the material is said to be subjected to combined stresses. Probably the most discussed instance of a case of this nature occurs in the combined bending and twisting of a crank-shaft; but to explain the gist of the

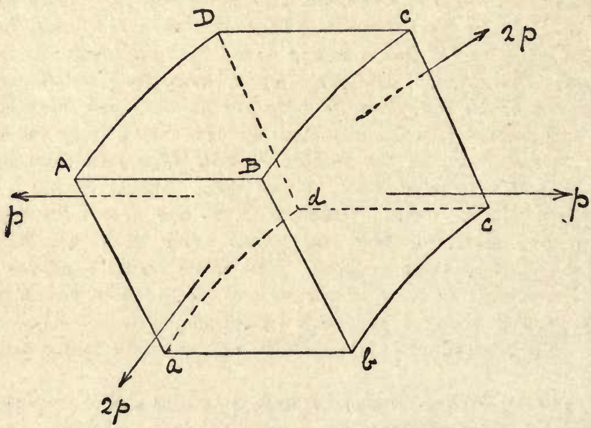


Fig. 125.—Section of Specimen under Compound Stress.

matter in a lucid way—so that those not previously conversant with the subject can appreciate it readily—we will first consider the case of a boiler without longitudinal stays.

Taking a small square (see Fig. 125) at the surface A B C D, we know that if A B and C D lie along the length of the boiler, then the surface A B b a (where a b c d is the inside surface with A B C D) is subjected to a tension hoop stress 2 p, and the surface B C c b is subjected to a length-ways tension stress p, as a result of the pressure inside the boiler. Thus the material is subjected to the combined stresses 2 p and p, both being

[1] This has been compiled from various contributions by the author to *Engineering* and papers which have been read on the subject before technical societies.

tensile. There is also a third stress, of varying amount, acting radially; but as this is at most only equal to the boiler pressure, we shall omit it for the sake of clearness.

Now, if we had the material of the boiler under the hoop stress $2p$ only, we should know what factor of safety the boiler would have, or what internal pressure it would stand without yielding, if we had made a test of the material in an ordinary testing machine. But when in addition to this hoop tension $2p$ we have a second stress p simultaneously applied at right angles to it, the question arises as to what effect it will have on the capability of the material to withstand the larger hoop stress.

It is evident that the direct experiment in the testing-machine will not tell us this; it applies one simple tension only.

The stress we are concerned with is the yield-point stress—*i.e.*, the stress at which rapid permanent change of shape takes place. This stress is now used as the basis in strength calculations, in place of the formerly used "ultimate strength."

A full discussion of the various theories which have been advanced for the failure of materials under combined stress would be out of place in this book, and the reader should refer to the numerous papers before the technical institutions and articles in the technical papers by Guest and others on this subject.[1]

It will suffice to say here that the tendency of modern research has been to demonstrate that for *ductile* materials such as mild steel failure under combined stress takes place when the maximum shear stress reaches a definite value, this shear stress being half the algebraic sum of the principal stresses. Or, expressed in symbols,

If p is the direct stress, and q the shear stress at right angles—

$$\text{Maximum shear stress} = \sqrt{\frac{p^2}{4} + q^2}.$$

The two principal stresses being $\frac{p}{2} + \sqrt{\frac{p^2}{4} + q^2}$ and $-\frac{p}{2} + \sqrt{\frac{p^2}{4} + q^2}$.

This failure under maximum shear stress has been aptly termed Guest's Law. The first experimenter to carry out research work in this direction, which can be taken to give a reliable basis for deduction, was Mr. J. J. Guest. The following description will indicate the method employed.

He arranged his tests upon hollow tubes, which he could subject to tension, torsion, and to internal fluid pressure; he thus obtained a series of varied combined stresses, from which the law given above was first deduced. The value of this indirect method is proved by the definite success of the investigation.

The specimen is placed in an ordinary single-lever testing machine,

[1] See Bibliography at end.

but between the specimens and the jaws of the machine are ball-bearings which would allow the specimen to turn easily while under the load of the testing machine. A bar passed through the top of the specimen served to apply the torque, a pair of bands running from the bar over pulleys, and were attached to another bar, to the centre of which loads were applied to produce the torque. The bottom of the specimen was prevented from turning by a bar which pressed against stops. The piping by which the fluid under pressure was applied to the interior of the specimen was used only in certain of the tests. The pressure in the piping was measured by a gauge. The specimens were tubes (of steel, brass, and copper), soldered on to holders at each end, and tension loads, torques, or internal fluid pressure were applied, both singly and in various combinations of two at a time.

To measure the strains and determine the yield-points in the various tests two instruments were used—namely, an extensometer, to measure the length extension of the specimen, and a torsion-meter. Both were optical instruments. The extensometer gave the mean axial extension, and was not affected by any bending or twisting of the specimen, and the tests of its accuracy indicated an extreme error of $\frac{1}{50000}$ in. only. The torsion-meter seems to have also been exceedingly accurate. Both instruments were "single reading"—that is, only one observation had to be taken to obtain the extension or twist on the specimen, and this evidently is of importance in determining yield-points.

Nine steel tubes were experimented upon, involving 101 different tests; each tube was experimented upon several times, the stress being taken off when the yield-point had been reached in any test. To explain the system of testing we will take the set of nine tests on tube No. 4 and examine them.

The first test was a torsion test. A small load torsion of 250 lbs. was put on a specimen to steady it. The loads producing the torque were then applied by uniform amounts and the twists of the specimen observed at each addition. On approaching the yield-point loads would be added more gradually, and the twist carefully watched for any continued yielding under a constant load. When this occurred, or the change of twist readings ceased to be proportional to the added load, the yield-point would have been reached, and owing to the thinness of the tubes this would be clearly defined. It occurred at a load of 90 lbs. The shearing stress was then 22,500 lbs. per sq. inch. The load was then removed. The next test was a tension test; in this case the extensometer readings were taken and the yield-point found to occur at a load of 4,000 lb., or a tensional stress of 41,200 lbs. per sq. inch. The third test is a combined torsion and tension test. The specimen was first gradually loaded with a torque load, and the twist read, but when 70 lbs. had been applied this loading was stopped and the tension load increased. Both the twist and the extension would have been read as these loads were added, and the twist reading should not change until the yield-point

is reached, which occurred at a load of 2,750 lbs., when the specimen would slowly yield, both by extending and by twisting, although no addition was made to the torque. The principal stresses would be calculated from the tension load and torque combined. They were 38,650 lbs. per sq. inch tension and 8,350 lbs. per sq. inch compression.

The fourth test was a combined tension and internal pressure test. In this case the tension load was added first, readings of the extensometer being taken to make sure that everything was working rightly. At a load of 3,000 lbs. this was kept constant, and the further stresses added by applying internal fluid pressure and gradually increasing it. When this fluid pressure was 1,150 lbs. per sq. inch the tube began to yield, both by stretching and increasing in diameter, and the loads were removed.

Test No. 5 was a torsion and internal pressure test; the torsion load was applied first to the amount produced by 75 lbs., and then the internal fluid pressure was applied.

Guest, when testing these tubes under combined tension and internal pressure, made due allowance for the increase of tension (longitudinal) due to the internal pressure. The tubes were sealed at the ends. In order to obtain the actual axial stress at any time, the axial stress p_1 due to the internal pressure was added to the axial stress p_0 due to the tension load on the machine. The actual axial stress was thus $p_1 + p_0$, and the circumferential stress $2\,p_1$. This is clearly stated by Guest in that section of his paper entitled "The Calculation of Stresses," and it is evident that if the specimens are definitely closed at the ends, then the actual stress is obtained by adding together the stresses due to the tension load and to the internal pressure. For tube No. 7, *e.g.*, there were two tests. In the first test the tube yielded to circumferential stress, and in the second to axial stress—the amounts of the stresses being interchanged. The results showed that the material was isotropic; tests on two other tubes confirmed this.

Some diagrams plotted from these three kinds of combined tests are given by Guest, and they give two strain readings and the load readings, and so represent the whole test very clearly. The material always appears to yield in the two ways simultaneously.

Test No. 6 was similar to No. 4, No. 7 to No. 3, No. 8 to No. 2, and No. 5 to No. 1.

Considering the maximum principal (tensional) stresses at the yield-point, we see that these varied from 22,500 lbs. per sq. inch in a torsion test to 42,900 lbs. in a tension and internal pressure test, or to 41,200 lbs. per sq. inch in the simple tension test. These quantities are in the ratio of 1 to 1·91 and 1·86.

Taking the maximum yield-point shearing stresses in the various experiments, these vary from 20,200 lbs. per sq. inch in the torque and internal pressure test to 22,500 lbs. per sq. inch in the simple torsion test, and these quantities are in the ratio of 1 to 1·11.

Table XXXIX.—Tabulated Results of some of Guest's Experiments on Steel Tubes.

Mean diameter = 1·250 in.
Thickness = 0·025 in.
Young's modulus (E) = 31,100.000 lbs. per sq. in.
Modulus of rigidity (K) = 11,170,000 lbs. per sq. in.
Poisson's ratio (σ) = 0·393.
P = testing-machine load in lbs. weight.
W = load-producing torque.
p_0 = Internal pressure in lbs. per sq. in.

Test No.	Applied Loads.			Principal Stresses.		Max. Shear.	Elongation.	
	P.	W.	p_0.	p_1.	p_2.		Experimental.	Calculated.
1	—	90	—	22,500	−22,500	22,500	0·001035	0·001005
2	4000	—	—	41,200	0	20,600	0·001385	0·001325
3	2750	70	—	38,650	− 8,350	22,500	0·001425	0·001350
4	3000	—	1150	42,900	24,000	22,000	0·001075	0·001078
5	—	75	1150	37,700	− 1,700	20,200	0·001250	0·001235
6	2500	—	1600	42,700	33,800	22,100	0·000940	0·000925
7	3400	50	—	39,000	− 4,000	21.500	0·001324	0·001305
8	4000	—	—	41,200	0	20.600	0·001388	0·001325
9	—	90	—	22,500	−22,500	22,500	0·001070	0·001005

The greatest extension at the yield-point may be arrived at in two ways; first, by taking the readings of the measuring instruments, and hence obtaining the extensions; or, secondly, by calculating the extension from the stresses and the previously measured elastic constants of the material. The first method has the advantage of being more directly experimental; but as the material will have suffered permanent stretching before the yield-point is definitely determined, it is hardly so fair a comparison as the second method. Taking the second method, the limiting extension varies from 0·000925 in the second tension internal pressure test and 0·001005 in the simple torsion test to 0·001325 in the simple tension test. These are in the ratios of 1 : 1·09 : 1 43.

The difference from constancy is nearly four times as great in the extension, and eight times as great in the principal stress as it is in the shearing stress. In the tests on the other tubes similar results were obtained, and Guest hence propounded the law that the shearing stress was constant, as being sufficiently accurate for engineering purposes, although he sets forth a nearer approximation should it be required for scientific purposes.

Besides the work of Guest several experimenters have since carried out work in the same direction.

In America, Professor Hancock has carried out an elaborate series of tests on steel tubes, a *résumé* and criticism of which was contributed by the author to *Engineering*, August 20, 1909. These tests give results which cannot be said to *prove* any of the theories at present enunciated. The following table compiled from the results published will indicate this:—

TABLE XL.

Specimens.	Average Variation from Mean per cent.		
	$\frac{p}{2}+\sqrt{\frac{p^2}{4}+q^2}$.	$\sqrt{\frac{p^2}{4}+q^2}$.	E × Max. Principal Strain.
	Rankine.	Guest.	St. Venant.
Nickel steel, solid round . .	11·2	13·1	7·7
Low carbon steel, solid rounds .	7	20	7
Steel tubing 1 in. outside diameter, 0·075 in. inside diameter . .	10·3	11·5	6·1
Steel tubing 1 in. outside diameter, 0·05 in. thick	13·8	5·2	8·7
Steel tubing 1 in. outside diameter, 0·25 in. thick	8·5	11·2	7·8
Low-carbon compression torsion .	6·7	16·2	4·7
Average of all tests . .	9·6	12·9	7

Mr. Walter Scoble has attempted to solve the problem by conducting tests on a material subjected to combined bending and twisting. It is a pleasure to be able to say that this work has been conducted in a very scientific manner. The following criticism refers only to the experiments on ductile materials under combined stress. His work on brittle materials is mentioned later.

The great difficulty which Mr. Scoble encountered was the location of yield-points. He very ingeniously attempted to obtain a fixed point for the yield. He found a decided elastic limit effect during all these tests, which he attributed to local yielding. He says[1]:—" If the material is satisfactory, the stresses at the elastic limit and yield-point are nearly proportional, and it makes little difference which is taken. Faulty

[1] *Philosophical Magazine*, vol. xii., p. 535.

specimens will usually have a low elastic limit, whereas the yield-point is little affected, and the same applies to changes in the metal due to any special treatment to which it may have been subjected. Taking these facts together, it is evident that the yield-point is much more nearly constant than the elastic limit, and in making a simple test it is correct to consider both points in relation to each other." With this probably all experimenters will be in complete agreement; the point of disagreement will be in the accurate determination of the yield-point. In Mr. Scoble's experiments there was more difficulty in getting a clearly-defined yield-

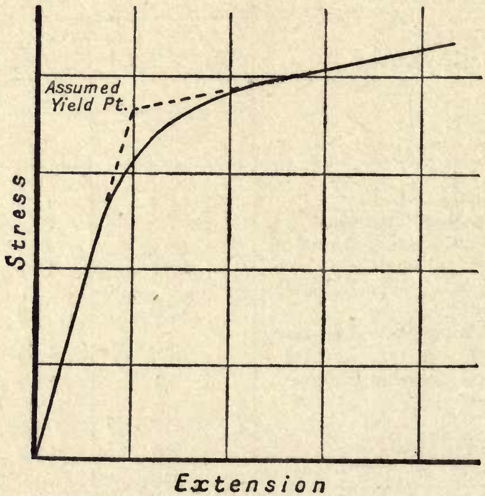


FIG. 126.—W. Scoble's Method of deciding Yield-Point.

point than when the material is loaded in direct torsion, or compression and torsion, because of the varying stress due to bending, as well as to torsion. It is true that his ingenious arrangement enables the same stresses to be obtained with smaller forces, but providing that the apparatus is available for a fairly uniformly distributed stress, it would appear more satisfactory to leave out the additional complication obtained during a bending test. What is doubtful is whether Mr. Scoble did obtain the real yield-point. His method is indicated in Fig. 126. He himself remarked concerning this method, "supposing this course was not justified, at least this is a definite, easily determined point to deal with, and any probable error would not be greater than that which is likely to arise when taking a point less closely defined." It is clear that he is not fully satisfied with this determination of yield-point.

A table of results obtained by Mr. Scoble is given below:—

TABLE XLI.—RESULTS OBTAINED BY MR. SCOBLE.

(Combined Bending and Torsion.)

Number of Tests.	p.	q.	$\frac{p}{2}+\sqrt{\frac{p^2}{4}+q^2}$.	$\sqrt{\frac{p^2}{4}+q^2}$.
I.	64,600	0	64,600	32,300
III.	0	29,170	29,170	29,170
IV.	16,220	28,250	37,500	29,400
V.	32,350	25,750	48,200	32,000
VI.	48,600	23,050	57,800	33,500
VII.	58,750	14,240	61,980	32,600
XII.	48,600	20,900	56,740	32,440
VIII.	62,100	7,840	63,080	32,030
IX.	56,100	16,220	60,450	32,400
XI.	35,330	24,700	48,060	30,400

Average variation from mean of maximum shear stress = 3·72 per cent.

It will be seen that in this case we have for the average variation from the mean for the whole of the tests:—Maximum shear stress = 3·72 per cent., maximum principal stress = 18·3 per cent. A study of the above facts reveals considerable evidence in favour of Guest's law for combined tension and shear stresses, and, but for the disturbing influence of Professor Hancock's experiments, this would satisfy many engineers. At the same time, we must bear in mind that if any general law for the failure of all materials is to be ascertained the results must include compression as well as tension data. Taken in conjunction with the results obtained by Guest, Scoble's experiments show that for design purposes Guest's law is true. So far, then, we have three experimenters who have published results; all three express opinions in favour of Guest's law, and two of them produce evidence in its favour. It is probable that, in connection with these tests, the engineer who has not attempted to conduct similar work underrates the difficulties.

It now remains to deal with the four points of great importance in all testing work, and which has possibly had an influence upon the results obtained during the combined stress experiments.

Elastic Limit and Yield-Point, and Ratio of $\frac{\text{Max.}}{\text{Mean}}$ Stress.—The chief difficulty arising under the first heading is the masking effect on the elastic limit due to variation in material and non-uniformity of stress. In any test variation of material will cause a greater variation in elastic limit than in yield-point. At the true yield-point the "time effect" is considerable, and the apparent yield-point, if obtained by the

drop of the beam, is higher than the true yield-point. In a tension or compression test it is essential to determine the maximum stress. The ratio of the maximum to mean stress will, of course, be much less when extreme precautions have been taken to ensure that the specimen is loaded axially. The result of non-axial loading is shown to scale in Fig. 127. But whatever precautions are taken, this ratio will never be

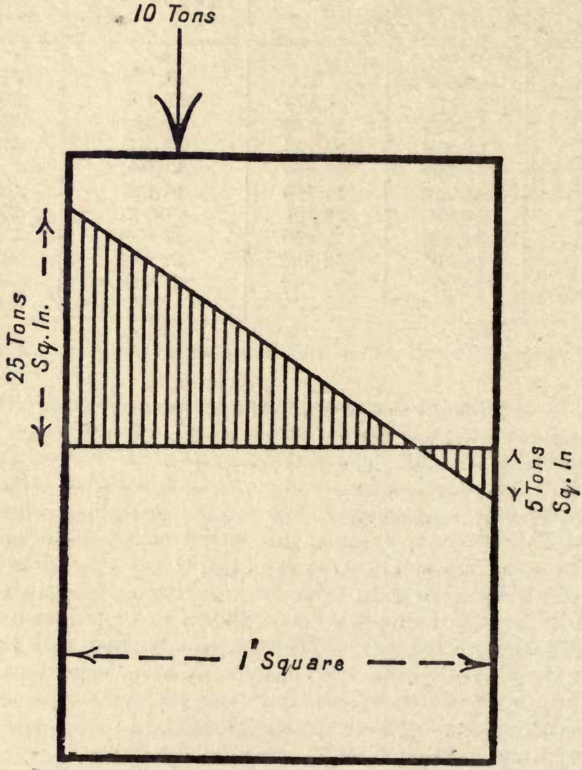


FIG. 127.—Distribution of Stress in Specimen subjected to Non-Axial Loading.

unity. With spherical seats, it would at first sight appear that an axial load is obtained, but this is by no means the case, as the results given below will show. Especially to be noted is the author's test A D,[1] which shows that a most unaccountable result might have been obtained, but for special precautions, when using spherical seats. It is therefore essential, in order to reduce this source of error to a minimum, to take measurements which will enable the ratio to be calculated. At

[1] *Engineering*, 1909.

present the only way of doing this seems to be by measuring strains in at least three planes round the specimen. Experiments show (and it can be readily theoretically demonstrated) that spherical seats merely form a flexible arrangement by which the specimen can be placed approximately truly in the machine; once the load is applied they do not move but accommodate themselves to the eccentricity of loading.

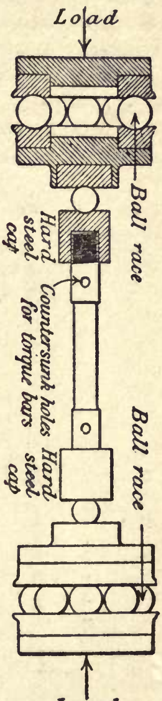


FIG. 128.—Arrangement of Loading for Combined Compression and Torsion Experiments.

Variation of Material Used.—In Prof. Hancock's Table II. there are tests on nickel steel solid rounds. This material is indefinite with respect to its elastic limit. The low-carbon steel is stated to be "from the same shipment." It is possible that, although there is little variation in specimens off the same bar, there is considerable variation in specimens off the same shipment, as there may have been a difference of temperature in rolling the material.

Time Effect.—The shape of the curves given by Prof. Hancock leads one to think that the loading was carried on at a fairly rapid rate. This is undesirable if the exact elastic limit is to be detected. Near the critical point the time influence is very great, especially in torsion tests, and the material will still appear elastic if time is not allowed for the specimen to over-strain. The point has been recently elaborated by the author in his paper before the Iron and Steel Institute.[1]

Determination of Yield-Point.—The validity of Mr. Scoble's method of determining the yield-point is based on the assumption that the relation of stress to strain is still linear after yield has been passed. The time effect after yield is, however, so great that it cannot be neglected, and the shape of the curve does not even approximate to a straight line.

A number of experiments on compound stresses have been carried out by the author, particulars of which will be found in papers read before the Technical Institutions.[2]

Preliminary experiments were made upon both solid and tubular mild steel specimens, and it was decided to use solid bars. In most of the author's experiments a specimen of 1 inch diameter was used. The length between the shoulders was 4¾ inches. The reason why similar specimens were used for torsion, tension, compression and combined

[1] "The Elastic Breakdown of Certain Steels," *Journal Iron and Steel Inst.*, No. 1, 1910.
[2] See Bibliography at end.

stress tests was that it was desired to make them interchangeable for elastic range tests. The ratio of the length to the diameter was sufficient to ensure that, unless the loading during a compression test was placed with considerable eccentricity, the yield-point in compression would be reached before the specimen failed as a strut. If the loading is directly through the axis of the specimen it is safe to make this ratio twenty for a mild steel specimen.

Previous experiments with various grips were made, and as a result the specimens were turned with screwed ends, gas-threads being used. The general shape of the specimen and the arrangement of the apparatus is indicated in Fig. 128 and Fig. 129. The screwed ends were carefully

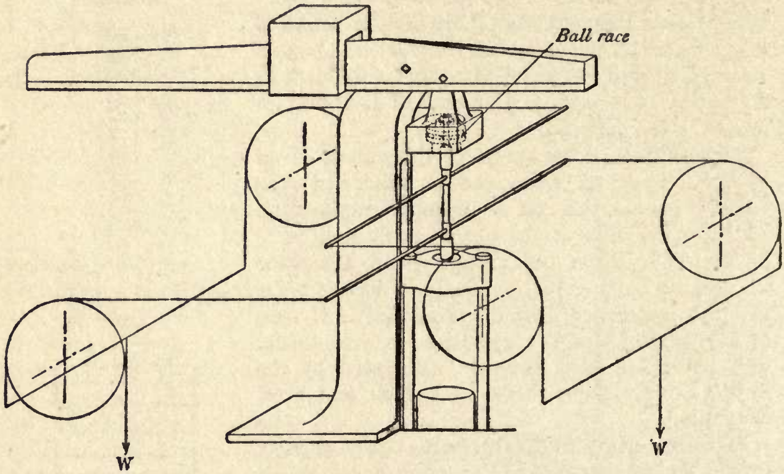


FIG. 129.—General View of Combined Tension and Torsion Apparatus, showing the Specimen with Torsion Bars and Pulleys.

fitted to the tension grips and the compression caps. The centre $4\frac{1}{2}$ inches of the specimen was turned parallel to 1 in 2,000. Torque bars were fastened by set-screws which fitted directly on to the specimen, at the top and bottom, as shown in Fig. 128.

A 50-ton Wicksteed testing machine was used for the application of tension and compression loads. Ball-bearings were fitted so that the specimen was free to revolve when tested in torsion.

The torque bars were flexibly coupled together and moved simultaneously, the friction of the ball-bearings being thus eliminated before a reading was taken.

Fig. 129 gives a general idea of how the torque was applied to the specimen. The torque arms were actually secured by means of set-screws let into countersunk holes in the specimen. From the end of each torque bar a cord was carried over a bicycle wheel and fastened to

a knife-edge upon which rested a hollow bar. A tray was hung by a knife-edge on the centre of this bar, and weights, marked W, were placed in the tray in order to apply a torque.

From the arrangements of the pulleys shown in the sketch it will be seen that every effort has been made to eliminate bending during the application of the torque. Owing to the longer distance between the points of support of the specimen, the stress caused by bending—due to bad application of the torsion load—is greater during a tension than during a compression test.

A probable source of error in Mr. Guest's experiments may now be explained. He used long torque bars at the top end of the specimen, and two shorter bars at the bottom end. These two lower bars were brought against stops. The advantage of this arrangement was that it was only necessary to use one tray and one set of weights, but it is probable that unbalanced bending stresses are thereby set up in the specimen, and the arrangement shown in Fig. 129 was therefore adopted. Strains were measured by means of the combined sphingometer described in Chapter IV. for both tension and torsion. By the use of ball-bearings in the testing machine and the pulleys the effect of friction was reduced to a minimum and was negligible. The sphingometer strips rendered it a simple matter to record very small strains.

In the experiments recorded (SS specimens) the elastic limit and the yield-point coincided. In the case of perfectly homogeneous specimens loaded in tension and compression in such a manner that the load passes through the axis of the specimen—and consequently there is no bending—the yield-point is marked by a rapid increase of stretch which takes place for a small addition of load. The author's experiments showed that the load never is acting exactly through the axis of the specimen. Some of the material used (SS specimens) was remarkably homogeneous,[1] but the load was always slightly non-axial. In such a case there will be an apparent "elastic limit effect" if an extensometer is used which merely measures a mean extension of the specimen. With non-axial loading, and a homogeneous material, the yield-point is reached at one portion of the specimen before the whole of it yields. With an extensometer which gives the distribution of stress, there will be an apparent rapid change in the eccentricity of loading directly any portion reaches the yield-point. Then will follow the "elastic limit effect" (during which the mean extension of the specimen is slowly increasing for equal increments of load) due to eccentric loading, and then will come the total yield shown by a great increase in strain. What has been recorded in these experiments is the maximum stress on the specimen when the first portion of it reaches the yield-point.

Until the load is reached at which this portion yields there seems to be no "time effect," but at this point that phenomenon becomes most marked.

The following table (on page 248) exemplifies the results obtained:—

[1] The term "homogeneity" is intended to include isotropy and uniformity.

TABLE XLII.—RESULTS OF SS STEEL (TESTS MADE AT THE EAST LONDON COLLEGE).

Specimen and Test.	Diameter.	Direct Load-tons + p Compression − p Tension.	Torsion Load. Lbs.	Ratio[1] of Maximum / Mean Longitudinal Strain.	p. Lbs. per sq. in.	q. Lbs. per sq. in.	Max. Principal Stress. $\frac{p}{2}+\sqrt{\frac{p^2}{4}+q^2}$.	Max. Shear Stress. $\sqrt{\frac{p^2}{4}+q^2}$.	Max. Principal Strain ×10³.	Torsion Slip. Approx.
SS I*a*	1·003	+ 0·5	96	1[1]	1,420	18,500	+19,250	18,540	0·813	1½ p.c.
SS II*a*	1·001$_7$	+ 0·5	98	1	1,420	18,960	+19,710	19,000	0·833	2 ,,
SS II*b*	1·001$_7$	+ 0·5	96	1	1,420	18,580	+19,330	18,620	0·817	1 ,,
SS II*c*	1·001$_7$	+ 8·0	74	1[2]	22,800	14,310	+29,700	18,300	1·052	6 ,,
SS III*a*	1·000	+ 8·0	72	1	22,800	13,920	+29,400	18,000	1·038	3 ,,
SS I*c*	1·003	+ 0·5	96	1	1,420	18,500	+19 250	18,540	0·813	20 ,,
SS I*d*	1·003	+ 0·5	94	1	1,420	18,110	+18,860	18,150	0·796	2 ,,
SS I*e*	1·003	+ 5·0	90	1	14,200	17,350	+25,850	18,750	0·970	20 ,,
SS IV*a*	1·002	+ 0·5	96	1	1,420	18,540	+19,290	18,580	0·816	2 ,,
SS IV*b*	1·002	+ 2·0	90	1·975	11,200	17,390	+23,860	18,260	0·916	2½ ,,
SS IV*c*	1·002	+ 4·0	88	1·15	13,080	16,990	+24,760	18,220	0·935	2½ ,,
SS IV*d*	1·002	+ 6·0	82	1·125	19,200	15,830	+28,100	18,500	1·017	2½ ,,
SS IV*e*	1·002	+ 8·0	65	1·089	24,750	12,540	+30,030	17,650	1·046	3 ,,
SS I*f*	1·003	+ 0·5	95	1	1,420	18,300	+19,050	18,340	0·805	9 ,,
SS V*b*	1·002$_5$	+ 0·4	98	1	1,140	18,910	+19,450	18,940	0·828	2 ,,
SS V*c*	1·002$_5$	+ 3·0	94	1·134	9,650	18,110	+23,545	18,720	0·917	2 ,,
SS V*d*	1·002$_5$	+ 6·0	86	1·111	18,930	16,590	+28,555	19,080	1·040	—
SS VII*a*	1·002	− 0·5	95	1	− 1,420	18,350	−19,080	18 390	0·817	2 ,,
SS VI*c*	1·003	− 7·0	68	1·192	−23,770	13,140	−29,600	17,720	1·088	6 ,,
SS VIII*a*	1·002	− 7·0	76	1·036	−20,570	14,660	−28,210	17,920	1·010	8 ,,
SP 4A	1·026	−12·7	0	1·129	−38,800	0	−38,800	19,400	1·284	—
SP 4B	1·026	+12·5	0	1·099	+37,250	0	+37,250	18,620	1·233	—
[3]MP 4	0·999	−12·7	0	1·065	−38,600	0	−38,600	19,300	1·278	—
MP 6	1·026	+13·5	0	1·050	+38,450	0	+38,450	19,220	1·273	—

Torsion slip is given as a percentage of total elastic strain.
p = Maximum direct stress on horizontal plane. q = Maximum shear stress on horizontal plane.

1 When given as unity exact value not known.

2 In these early tests the stress distribution was not calculated, but a fair average value is taken now, in which case the shear stresses for Tests SS II*c* and SS III*a* are 18,900 and 18,700. Average variation from mean of maximum shear stress is 1·96 per cent.

3 Curves for these tests are shown in "Method of detecting the Bending of Columns," Proceedings Inst. Mech. Eng., 1908, Part 3, Figs. 4 and 6 (pp. 700—701).

Fig. 130 shows the results of this table, together with others obtained by the author, plotted in a manner showing very clearly the agreement with Guest's law. The latter would give an exact circle.

A Combined Stress Test fully worked out.—*Specimen SS V, Test c.*—Length of specimen between points = 3·903 inches. Diameter, 1·0025 inch. Length of torque bars = 76·4 inches. Distance of sphingometer strips from axis of specimen = 2·58 inches.

Calculations for Tension or Compression Test.—The following readings and calculations were made :—

	Strip No. 1.	Strip No. 2.	Strip No. 3.
Scale Readings. Compression load 0·5 tons . . .	238	281	332
Scale Readings. Compression load 3 tons	130	234	134
Calibration equivalent of scale divisions in inches . .	0·00000776	0·00000917	0·00000752
Extension of strips in inches for load of 2·5 tons . .	0·000838	0·000431	0·001489
Surface extension in inches .	0·000903	0·000824	0·001030

From the above the mean extension = 0·000919 inch, whence E = 30·2 × 10^6 lbs. per sq. inch.

The maximum surface extension[1]=0·001041 inch, whence ratio $\frac{\text{maximum stress}}{\text{mean stress}}$ on surface perpendicular to axis$=\frac{1041}{919}=1·134$.

Torsion Test.—Calibration of torsion strip gave 1 division = 0·00001986 radians.

A compression load of 3 tons was kept on the specimen and the torque applied by adding weights to the trays.

It was found that an increase of 70 lbs. caused a deflection of 447 divisions.

$$\text{Whence strain}=\frac{0·501 \times 447 \times 0·00001986}{3·903}$$

$$\text{Torque}=\frac{70 \times 76·4}{2}=\frac{\pi}{16} f\, d^3$$

$$\text{whence } f = 13{,}510 \text{ lbs. per sq. in.}$$

$$C = 11·87 \times 10^6 \text{ lbs. per sq. in.}$$

$$\text{Now since } (1+\sigma)\, 2\, C = E \therefore \sigma = 0·298.$$

[1] Calculated as explained in "Compound Stress Experiments," Proc. Inst. Mech. Eng., 1909.

Stresses at Yield-Point.

$$p=\frac{3\times 2240\times 4}{\pi\times 11005}\times 1\cdot 134=9{,}650 \text{ lbs. per sq. in.}$$

p = 18,110 lbs. per sq. in.

∴ Maximum shear stress = 18,720.

Maximum principal stress = 23,540.

Maximum principal strain = $0\cdot 917 \times 10^{-3}$.

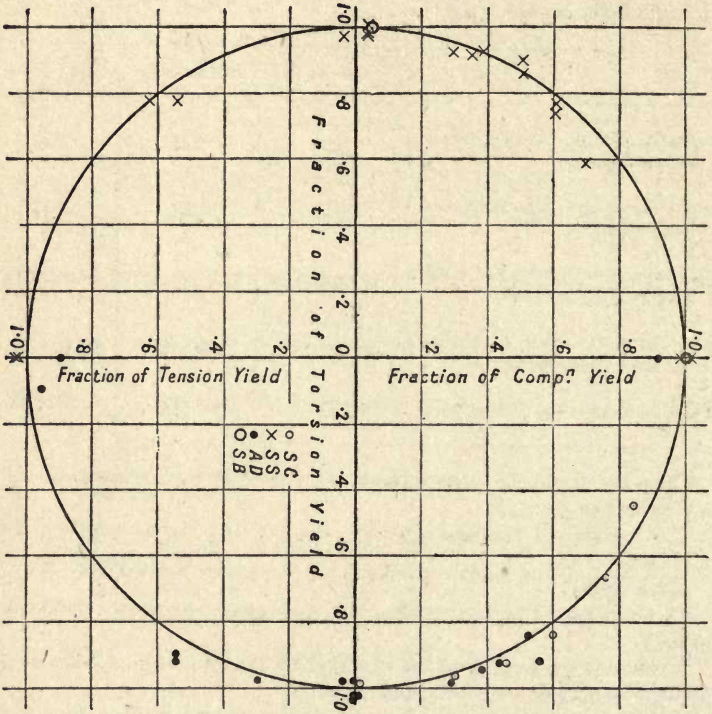
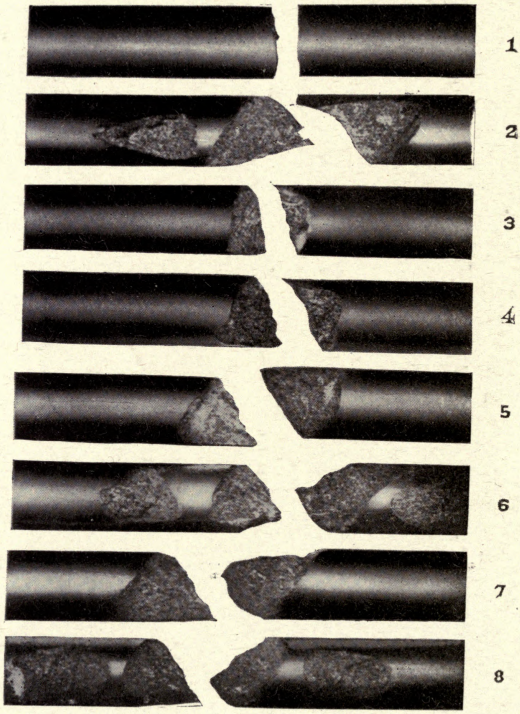


FIG. 130.—Curve showing Method of Plotting Results of Compound Stress Experiments.

Mr. Mason's Experiments.—At the University of Liverpool Mr. William Mason, M.Sc., has made experiments upon tubes subjected to compression and internal or external fluid pressure. An ingenious apparatus for holding the tubes in tension was also designed. Mr. Mason recognised the great necessity for, and difficulty of, obtaining axial loading in compression. There was also very considerable trouble in making reliable tests under simultaneous axial and hoop compression. However, most of these were overcome. The experiments recorded in



Fracture of Cast-Iron Specimens in Combined Torsion and Bending.

PLATE IV.

Mr. Mason's paper "show an approximate agreement between the maximum shear-stress at the yield-point in compression and the yield-point in pure shear, the mean difference in the tests of annealed specimens being about 3 per cent." Mr. Mason concludes by saying: "It appears, then, that mild steel in direct compression yields by shearing; and to a first approximation that the value of this shear-stress is independent of any normal compressive stress on the planes of the slide."

It is worth noting that the Report of the Steel Committee of Civil Engineers, as far back as 1870, included results which show very close agreement between the yield-stress in tension and compression of steel and wrought-iron bars.

Guest's Law.—It is suggested that the bulk of the evidence furnished by these experiments proves that Guest's law for the failure of ductile materials is accurate enough for design purposes.

Brittle Materials.—Mr. Walter Scoble and Prof. Goodman (of the University of Leeds) have made experiments upon brittle materials such as cast iron and hard tool steel. They find that at failure the maximum principal stress is constant. Fracture is the most satisfactory criterion of strength for a brittle material. The table on page 252, from Mr. Scoble's latest tests, supplies evidence to justify his conclusions. It is from a paper recently (1910) presented to the Physical Society.

Plate IV. shows the type of fractures obtained.

Prof. Goodman has made experiments and has published the following table, showing the relation between the angle of fracture and the principal stresses for cast-iron bars:—

TABLE XLIII.

Twisting Moment. Lbs. in.	Bending Moment. Lbs. in.	Equivalent Twisting Moment.	Modulus of Rupture. Tons per sq. in.	Angle of Fracture.	
				Actual.	Calculated.
Zero	2,300	4,600	25·5	0°	0°
777	1,925	4,000	26·7	12°	11°
1,170	2,240	4,750	27·1	14°	14°
1,228	2,255	4,820	23·1	17°	15°
1,308	2,128	4,628	24·0	19°	16°
2,606	1,375	4,320	20·8	33°	31°
2,644	766	3,520	16·2	38°	37°
3,084	Zero	3,084	16·0	43°	45°
Pure shear.			13·0	0°	0° } Mean of numerous tests.
,, tension.			11·5	0°	0°

COMBINED STRESS TESTING MACHINE.

A machine has been erected at the Glasgow and West of Scotland Technical College designed to give combined tests in tension and torsion.

TABLE XLIV.—HARDENED CAST STEEL BARS. $\frac{3}{4}$ INCH DIAMETER. EFFECTIVE LENGTH AS A BEAM 30 INCHES.

Bar.	Bending Moment. Lbs. in.	Torque. Lbs. in.	Tensile Stress due to Bending. Lbs. per sq. in.	Shear Stress due to Torque. Lbs. per sq. in.	Maximum Principal Stress. Lbs. per sq. in.	Minimum Principal Stress. Lbs. per sq. in.	Stress Difference = twice Max. Shear Stress.	Remarks.
1	935	6,200	12,720	75,400	82,060	—69,340	151,400	Low.
1	2,960	0	72,000	0	72,000	0	72,000	Correct.
1	3,570	0	86,850	0	86,850	0	86,850	High.
3	1,770	5,040	43,000	61,200	86,450	—43,450	129,900	Low.
3	2,880	0	70,000	0	70,000	0	70,000	Correct.
3	0	6,410	0	78,000	78,000	—78,000	156,000	Low.
4	2,350	3,940	57,150	47,900	84,350	—27,150	111,500	Correct.
4	0	5,860	0	71,250	71,250	—71,250	142,500	Low.
4	3,330	0	81,000	0	81,000	0	81,000	High.
9	2,360	4,750	57,400	57,700	93,200	—35,800	129,000	Correct.
9	0	6,280	0	76,400	76,400	—76,400	152,800	Low.
9	3,450	0	83,900	0	83,900	0	83,900	High.
12	0	6,020	0	73,200	73,200	—73,200	146,400	Correct.
12	3,090	0	75,100	0	75,100	0	75,100	High.
2	4,500	2,960	109,400	36,000	120,200	—10,800	131,000	Correct.
2	4,650	0	113,000	0	113,000	0	113,000	High.
6	2,170	1,660	52,750	20,200	59,600	— 6,800	66,400	Correct.
6	0	4,190	0	50,900	50,900	—50,900	101,800	Correct.
11	2,215	0	53,850	0	53,850	0	53,850	Correct.
11	0	3,900	0	47,500	47,500	—47,500	95,000	Correct.

It will make tension tests up to 56,000 lbs. and torsion test up to 12,500 inch-lbs. It consists generally of an arrangement of levers and steelyards by which both the tests are indicated separately and simultaneously, and an arrangement of worm and worm-wheel gearing to give the torsional test, the tension test being applied by means of a hydraulic cylinder and ram. The torsion stress is applied by hand power while the tension test is effected by the use of the town main pressure of 850 to 1,120 lbs. per sq. inch.

The specimen is of a maximum length between shoulders of 30 inches, the largest diameter being 1 inch. The specimen may be of the round type, which would be made with square heads, or they may be triangular or rectangular in section, in which case the specimens would not be provided with heads. Either of the foregoing specimens can be gripped between hardened steel wedges having serrated faces. The serrations secure the specimen from slipping during the tension test, while the tendency to rotate is resisted by a square recess in the torsion shaft in which the head of the specimen fits. The recess is adapted to receive various sections of specimens by the insertion of packing dies having recesses to suit the particular section of specimen. Three pairs of packing dies are supplied with the machine.

The tension test is applied by means of a double-acting hydraulic cylinder and ram. The cylinder is arranged to be worked by the hydraulic pressure from the town mains at 850 to 1,120 lbs. per sq inch. The piston has a stroke of 2 feet 10 inches, which allows 2 feet 4 inches for adjustment for different lengths of specimens and 6 inches more for the extension upon the maximum specimen. The piston rod is connected to the tension shaft by means of a swivel coupling containing ball bearings. The tension shaft has keyed upon it a worm-wheel, having machine-cut teeth, which is revolved by a worm-wheel upon the shaft of which a hand-wheel is secured. The whole of the arrangement of worm gearing is carried in a bracket which is mounted upon a sliding base. The sliding base has a machined underface and has a groove which clips machined guides upon the upper face of the bed.

The torsion test is applied by means of a worm and worm-wheel. The worm-wheel revolves in ball-bearings to reduce the friction caused by the tension test.

The specimen takes up the torque by means of a square shaft sliding in a sleeve, upon which the main torsion lever is keyed. This shaft is allowed to move slightly in a longitudinal direction by an arrangement of hardened steel rollers. These rollers bear against rectangular projections upon the shaft, and while allowing the longitudinal movement due to the tension test to take place, at the same time resist the tendency of the shaft to rotate inside the sleeve.

The sleeve of the torsion shaft is mounted upon ball-bearings which run in hardened steel races carried by a short cast-iron column which is bolted down to the bed.

The sleeve is connected by means of a ball-bearing muff to the main link which communicates the tension stress to the main lever for the tension test. Any rotary tendency upon the part of the muff is resisted by means of check links. The hand-wheels for propelling the poises for the two steelyards are placed close together so as to be worked by one man. The two steelyards are so placed that neither interferes with the readings upon the other. The details of this machine were supplied by the makers (Messrs. Avery), from whom, doubtless, more details can be obtained.

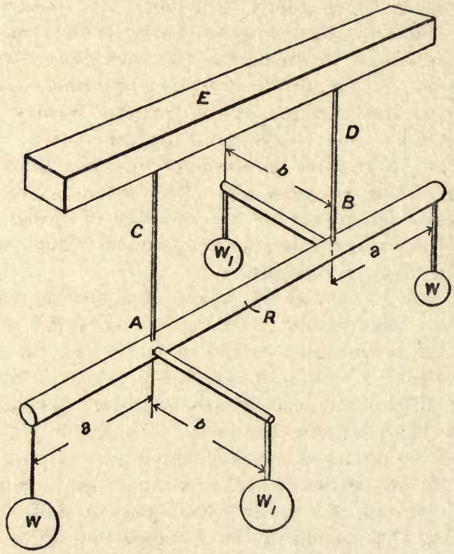


FIG. 131.—Diagram to show Method of Loading in a Combined Bending and Torsion Test on Dr. Coker's Apparatus.

So far as the author is aware no actual results on combined stress carried out on this machine have been published.

The details of an arrangement for making combined stress tests with the ordinary vertical testing machine, used with some success at the East London College (Fig. 129), are simple and easily made.

A Combined Torsion and Bending Machine.—Prof. E. G. Coker has designed an apparatus by which tests can be performed in combined bending and torsion. The principle on which the design is based is illustrated by Fig. 131, in which the rod R is suspended at intermediate points A, B, by wires C, D, depending from a fixed support E. The equal overhanging ends of the rod are loaded by weights W, so that the applied couple between the points of support is uniform and of amount Wa, where a is the length of the lever-arm. The rod is also twisted by weights W_1

attached to equal arms of length b, so that there is a uniform twisting moment of amount W_1b between the points of suspension. The two systems of loading are independent, and their ratio can be adjusted to any value desired.

In carrying out this arrangement in practice it is convenient to arrange that one of the levers for applying the twisting moment shall always remain in a horizontal position, and that the other shall be capable of turning through an arc to bring the first lever back to zero after each application of the load. The most convenient way of carrying this out is to replace the adjustable lever by a worm and worm-wheel gear secured in a casing and turned by a hand-wheel (see Fig. 132). To allow freedom for bending, the worm-wheel casing must be pivoted to rotate around a line intersecting the axis of the specimen and perpendicular thereto, and this method of pivoting must also be adopted at the horizontal lever. This arrangement only differs from that of the perfectly freely suspended arrangement shown in Fig. 131 in fixing one point of the rod, and this has the indirect advantage of stilling vibration, which is troublesome in the freely suspended bar.

The various parts are supported in a built up frame consisting of two planished steel shafts A secured in cast-iron cross frames B mounted on four standards, one of which latter is adjustable in height to secure steadiness on an uneven floor. Upon the steel shafts are two castings C, D, each of which has a cylindrical bearing E encircling one of the shafts and resting with a flat face F in line contact with the other shaft, and secured in position by a cross-bar G threaded on studs. This connection is perfectly rigid, since it removes all degrees of freedom and it is readily released by simply turning back one of the cross-bar nuts, leaving the casting free to slide into a new position. It also has the advantage that no accurate fitting is required for the supporting frame. The casting C, carrying the worm-wheel gear W has trunnion bearings H at right angles and to intersecting the axis of the specimen. The bearings are fitted with friction rollers, and when the machine is used simply for torsion the worm-wheel is kept in a vertical position by an arm I keyed to the bearing H and locked in position by a thumb-screw. A weight J attached by an arm to the second bearing balances the pivoted casing in all positions.

The weight levers are supported from a vertical standard K of the frame D by a wire L, terminating in a thin plate M with a keyhole slot encircling the spindle N. Formerly a roller bearing was used for this spindle, but this is an unnecessary refinement as the friction is extremely small, and can be easily taken into account. The casting supported in this way has three levers, P, Q, and R, the first two of which are for the application of twisting moments, and the third R, in the line of the specimen, is for applying a bending moment.

All the loading levers are provided with knife-edges, of circular form, made by turning an ordinary Whitworth nut down to form a disc with a V-shaped edge. These discs carry rings T with wide-angled

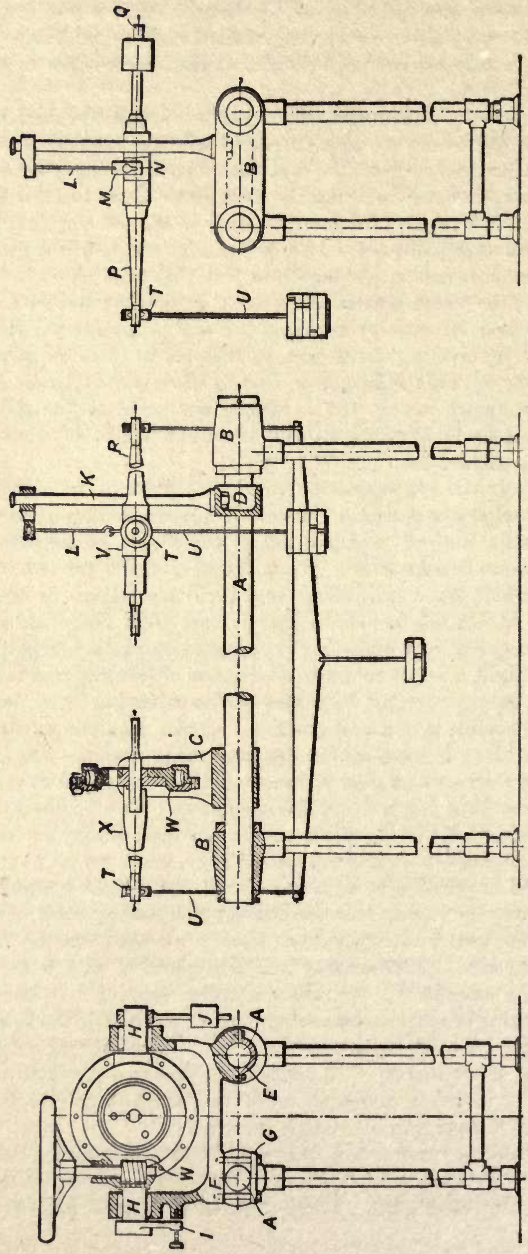


FIG. 132.—Professor Coker's Apparatus for Combined Bending and Torsion.

V-shaped recesses on the inner sides, and light rods U screwed into these rings carry the weight. This arrrangement of knife-edge is very easy to adjust accurately, and when bending and twisting stress are applied simultaneously the rolling line contact adjusts itself to the bending and twisting of the specimen. The bending of the specimen causes a change in the effective arm of the bending levers, which is generally negligible, but a correction may be necessary with a very long specimen. For if a is the length of the lever arm and b is the radius of the circular knife-edge, an angular deviation of amount θ will cause a change of $a-(a \cos \theta + b \sin \theta)$ in the lever-arm, and this is zero when $\theta = 0$, and also when $a = a \cos \theta + b \sin \theta$. In one machine built to this design the correction curve came out as given in Fig. 133. In the majority of tests the angular

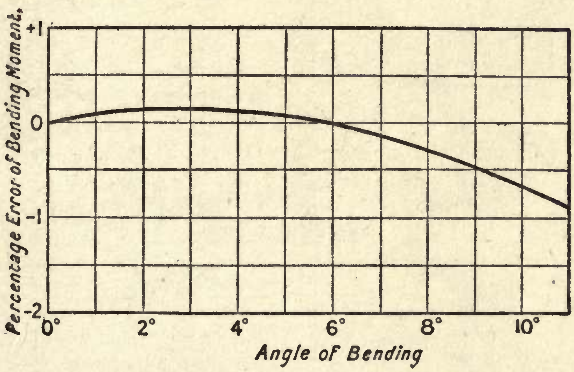


FIG. 133.—Curve of Correction Factor for Professor Coker's Combined Bending and Torsion Machine.

change at the ends rarely exceeds 5°, and the correction is therefore so very small as to be practically negligible.

The worm-wheel W and the casting V for the weight-levers are bored out to receive the ends of the specimen, and are provided with fixed keys which slide in corresponding key-ways cut in the specimen. When tubes are subjected to stress they are provided with solid ends secured by transverse pins, thereby avoiding brased joints, since these latter are troublesome, owing to the state of the metal being altered by the brasing. The end of the specimen projecting through the worm-wheel is fitted with a lever X for applying bending moment, and both levers for bending may be loaded independently or by a cross-bar suspended from stirrups as shown in Fig. 132.

Fig. 132 shows three views of a machine built on the principle here described. The actual machine shown is one built by students of the City and Guilds Technical College, Finsbury.

Prof. E. G. Coker's Instrument for Measuring Torsion and Bending Strains.—This instrument was originally designed to measure the angle of twist within the elastic limit, but the design shown can be adjusted in a few seconds for measuring the angular change due to bending. The calibration of the readings is effected on the specimen and serves for both bending and twisting. Fig. 134 shows the apparatus in part longitudinal section.

It consists of a graduated circle A mounted on the specimen B by three screws C in the chuck-plate D. A sleeve E provided with three screws grips the specimen at a fixed distance away from the first set.

The spacing of these two main pieces on the specimen is effected by a

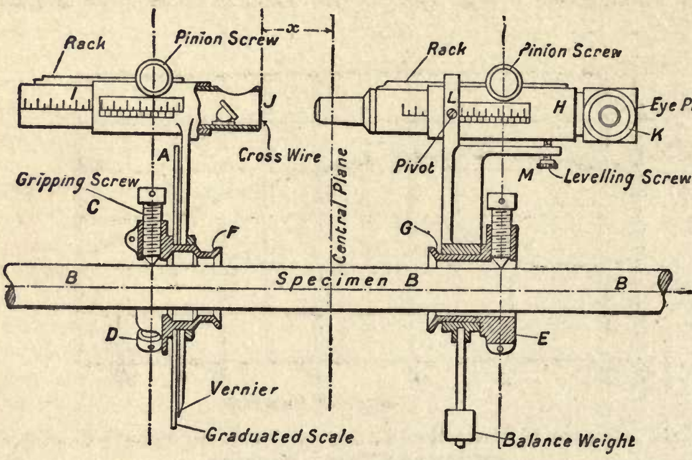


FIG. 134.—Professor Coker's Torsiometer for Measuring Strains in a Combined Bending and Torsion Test.

clamp, not shown in the figure, which grips the double cones F, G, and maintains them at the correct distance apart, until the set screws are adjusted.

The clamp is afterwards removed, leaving the plane of the graduated circle perpendicular to the axis of the specimen and the sleeve correctly set and ready to receive the reading-microscope H.

The vernier plate carries a sliding tube I, on which a wire J is mounted, and the movement of this latter due to bending or twist is measured by a scale in the eye-piece K, the divisions of which are calibrated by reference to the graduated circle. It is found convenient to have the microscope-tube pivoted about an axis perpendicular to its central line at L, so that any slight difference due to imperfect centering can be adjusted by the screw M to make the calibration value agree for a series of specimens.

The observation wire may be set at any convenient position for calibration, but for observations of the angle of twist when the specimen is also subjected to a uniform bending moment the wire should be in the central plane perpendicular to the specimen. For if the bending is in the plane containing the axis of the specimen and the observation wire, it has the effect of causing new parts of the wire to come into vi w on the scale, but no error is caused thereby. If the specimen is bent in a plane at right angles to the former, then the change in the reading is $(\theta-\phi)l$, where θ and ϕ are the alterations of angle at the ends and $2l$ is the length of the specimen under observation. Since the bending is uniform $\theta=\phi$ and no correction is necessary. Bending in any other plane can be resolved into components in the vertical and horizontal planes, and therefore falls under the preceding cases. In order to effect the adjustment required, both the wire and the microscope slide in adjustable tubes provided with graduated scales, and the movement to bring the wire into focus, is divided between them. To check the setting of the wire in the central position it is convenient to apply a uniform bending moment, and then to observe if any change takes place in the reading. The position for no change in the reading can be found in a few seconds.

In experiments where the bending moment is constant and the twisting moment is varied, no adjustment is practically required during the elastic life of the specimen; and even when the bending moment is variable the adjustment is practically negligible, as the length of the specimen under test is only a few inches.

The instrument is used for observations of the angular change due to bending by adjusting the wire in the horizontal plane passing through the axis of the specimen, and at a fixed distance away from the central plane, as shown in Fig. 134. Thus if the wire is at a distance x from the central plane, and the specimen is subjected to a uniform bending moment, the reading will be $(l+x)\,\theta-(l-x)\,\theta=2x\theta$, and this is a measure of the angular change θ between the ends, since any further corrections are negligible for elastic strains.

The instrument may therefore be used for measuring strains due to bending or twisting, and the single calibration required for both sets of readings is effected when the instrument is in position on the specimen.

Further Researches.—Although the laws for the failure of mild steel and very brittle materials (cast iron and hardened tool steel) are now established, it yet remains to be shown whether other materials fail by these laws. The effect of repeated stress upon ductile materials, and its bearing upon failure under combined stress, also requires investigation. There are numerous original experiments for those having the requisite facilities.

APPENDIX IV.

HEAT TREATMENT OF STEELS.

It is impossible, in this book, to give a full account of the work done on heat treatment of various steels. However, Prof. A. McWilliam and Mr. E. J. Barnes, of the University of Sheffield, have recently published[1] a very complete study of the effect of heat treatment on Bessemer steels, and the following facts, abstracted from their paper, will serve as a guide for work, either upon similar material or some other types of steel. The tests were made on ordinary commercial English acid Bessemer steels of carbon content varying from 0·10 per cent. to 0·86 per cent. The steels were received and treated in the form of forged or rolled bars 1 inch round, and either as received or after the treatment detailed were all tested in tensile, and as far as possible also under Dr. Arnold's alternating stress test, and were examined under the microscope.

Treatments with Distinguishing Letters.

Treatment.	Letter.
As received	B
Normalised. 950° C. for 20 minutes and cooled in air .	BN
Annealed. Slowly heated up to 950° C.; kept at 950° C. for about 35 hours; very slowly cooled down in furnace	BA
Quenched from 850° C. in water and tempered at 400° C.	BY
,, ,, ,, ,, ,, ,, 500° C.	BX
,, ,, ,, ,, ,, ,, 600° C.	BZ
,, ,, ,, ,, ,, ,, 700° C.	BW
,, ,, 900° C. ,, ,, ,, 600° C.	BJ
,, ,, ,, ,, ,, ,, 700° C.	BK
,, ,, 950° C. ,, ,, ,, 700° C.	BH

Some typical curves of this series were given in Fig. 68, page 105.

Methods of Experiment.—All steels were in the form of 1-inch round bars, and were sawn into lengths of about 11 inches. Some of the harder steels showed a peculiar structure after being sawn off, the sawn surface exhibiting a curious pattern of intersecting elliptical elevations about ⅛ inch broad. These gave no indications of their presence in the polished and etched micro-sections.

[1] Iron and Steel Institute, May, 1909.

Normalising.—The pieces were placed in a Fletcher gas muffle at about 750° C., slowly raised in about half-an-hour to 950° C., and so maintained for twenty minutes. They were then taken out, reared on end on firebricks, and allowed to cool in the air.

Annealing.—Annealing was carried out in a coal-fired reverberatory furnace, according to the details described in the general table of treatments.

Quenching.—The bars were heated in a Brayshaw salt bath furnace, the temperature of which was simultaneously determined by a platinum resistance pyrometer with Whipple recorder and by a Paul Pt. — Pt.— 10 per cent. Ir. thermo-couple, the latter calibrated by means of sulphur (444° C.) and silver (962° C.). When the temperature was kept steady these two pyrometers were in remarkably close agreement, but, as was to be expected, on a falling temperature the readings of the former were somewhat higher, and on a rising temperature a similar amount lower than those of the latter. The pieces were put in the bath when it had attained a temperature of about 50° C. lower than the quenching temperature desired; the heat was gradually raised to the temperature and maintained for fifteen minutes, when they were rapidly withdrawn and instantly quenched in pure Sheffield water at 15° to 20° C. The molten salts entirely prevented scaling, and thus the quenching was as efficient as the temperature used, compared with the size of the bars, would admit.

As much that is misleading has been published on hardening, the subject is considered shortly here as it is involved in the reasons for choosing a hardening temperature of 850° C. for the majority of their quenchings. In ordinary hardening it is essential that the piece of steel should be heated to a temperature such that when quenched it will throw off its scale, or "shale" as the hardener calls it. If any of this scale remains firmly adhering, whether from the nature of the steel or the temperature used, then it acts as a blanket over the part of the steel it covers, prevents efficient quenching, and the part underneath this scale will be soft. A hardening temperature which results in the steel properly shaling is also in general a temperature that will give efficient quenching; but when steels are heated, as in a salt bath, so that no scaling takes place, an efficient quenching temperature seems to be a function of the dimensions of the cross-section of the steel, for steels of the same composition and previous treatment. Even when bars were put into the salt bath with the original rolling-mill scale on them the molten salt seemed to remove it during the heating process.

Experience with hardening steels of various sections led the authors to consider 800° to 850° C. a suitable range, and as some of their steels were very mild they decided on the higher limit, 850° C., for their preliminary series of tests. This was fixed only in consultation on hardening work done, and not from the study of the previous work of others which had been read as it came out. The previous work was re-read only immediately before writing the paper, so the coincidence of the

choice of 850° C. with the opinions of such a vigorous and reliable worker as Wahlberg after reviewing his own elaborate series, done from an entirely different standpoint, is of great interest.

Tempering.—With one exception the tempering was done by putting the bars in a lead bath at the required temperature, and maintaining the bath at a constant temperature for fifteen minutes, when the bars were removed and cooled in the air. In carrying out this treatment it is necessary to remember that samples of steel float in molten lead like wood in water, and that some efficient means must be adopted for pressing them down into the liquid lead. The tray of the Brayshaw furnace weighted with a billet on the top part of the frame outside the bath was used with success. The exception mentioned above arose as follows:—

It was desired to save the trouble of holding the pieces down in the bath whenever possible, and hence as the Brayshaw mixture of one molecular weight of potassium chloride (74·5) to one molecular weight of sodium chloride (58·5), or in the proportion of about 2½ lbs. to 2 lbs., melts at about 650° C., it was thought that the tempering at 700° could be easily done in this bath. He who taketh short cuts seeketh trouble. The bath was steadied at the exact temperature, and the pieces put in and kept fifteen minutes at 700° C., but on endeavouring to get them out it was found that with the whole furnace cooling, the top had become pasty, and ultimately set before they could be removed; so that it was necessary to put on a little more gas, and, after re-melting the bath, keep agitating the whole right up to the top and thus get the bars removed. The total operation took forty-five minutes, during which the pieces had been down to about 600° C. and then up again to 700° C. Unless the recently described potassium bichromate and potassium chloride mixture, which melts at 360° C., proves to be non-oxidising tc steel immersed in it, the authors are likely to use a metallic bath only for future temperings.

The tensile test-pieces were all turned to 0·564 diameter and 2 inches parallel, and the tensile piece was turned as near as possible to one end, so that after fracture the other end was long enough to turn to the standard alternating stress test-piece, namely ⅜ inch diameter by 6 inches long. The micro-sections were cut off the unstrained part of the short end of the tensile test-piece. Thus the alternating stress tests and micro-sections were not off duplicate bars put through the same series of operations, but by the methods adopted represent tests actually off the same piece.

The composition of one of the steels[1] with regard to carbon and manganese is given on page 263, the carbon being determined by combustion and checked.

[1] The original paper contains records of several steels, but one type only is given here.

TABLE XLV.—SHOWING EFFECT OF HEAT TREATMENT ON STEEL OF CARBON 0·10 PER CENT. AND MANGANESE 0·56 PER CENT.

Treatment.	Mark.	Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation. Per cent. on 2 in.	Reduction of Area. Per cent.	Dr. Arnold's Alternating Stress Test.
As received .	10 B	19·1	25·9	37·1	63·4	—
Normalised .	10 BN	18·5	24·8	37·4	59·8	—
Annealed . .	10 BA	9·6	21·0	43·8	72·0	352
850° C. water and 400° C. air	10 BY	17·9	27 4	39·0	72·9	—
850° C. water and 500° C. air	10 BX	17·6	26·0	38·0	74·7	336
850° C. water and 600° C. air	10 BZ	19·4	26·0	38·5	71·6	326
850° C. water and 700° C. air	10 BW	16·7	26·1	40·0	74·5	331
950° C. water and 700° C. air	10 BH	21·1	28·4	35·0	67·5	239

TABLE XLVI.—THE EFFECT OF HEAT TREATMENT ON STEEL OF CARBON 0·29 PER CENT. AND MANGANESE 0·92 PER CENT.

Mark.	Yield Point. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation per cent. on 2 in.	Reduction of Area per cent.	Dr. Arnold's Alternating Stress Test.
30 B	26·6	40·9	25·0	46·8	322
30 BN	25·7	40·8	26·3	53·5	329
30 BA	21·5	37·1	26·5	48·6	296
30 BW	37·0	45·7	25·3	57·8	202
30 BJ	50·9	57·5	17·3	48·6	173
30 BK	46·2	54·3	19·5	50·8	184

The table containing the 30 B results shows the very marked influence of the higher quenching temperatures, namely, 900° for 30 BJ and 30 BK, even after these have been tempered at 600° and 700° respectively; for example, the high reduction in area, 51 per cent., for a 54-ton steel with yield point 85 per cent. of the maximum stress.

As showing the effect of heat treatment on other than Bessemer steels the following table from a paper on "High Tension Steels,"[1] by Mr. Percy Longmuir, B.Met., read before the Iron and Steel Institute, is instructive:—

TABLE XLVII.—5 PER CENT. NICKEL STEEL.

No.	Treatment.	Elastic Limit. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation per cent. on 2 in.	Reduction of Area per cent.
23	As received	47·6	56·96	13·5	20·0
24	Air cooled from 800° C. .	34·8	49·08	18·0	38·0
25	Heated to 1,000° C., quenched in oil at 1,000° C., tempered at 490° . . .	64·8	76·00	12·5	43·6
26	Heated to 1,000° C., quenched in oil at 1,000° C., tempered at 490° . . .	68·4	70·92	10·0	37·6
27	Heated to 1,000° C., quenched in oil at 900° C., tempered at 490°	66·8	70·08	12·5	45·2
28	Heated to 1,000° C., quenched in oil at 950° C., tempered at 490°	Not detected	82·56	1·5	0·4
29	Heated to 800° C., quenched in oil at 800° C., tempered at 490°	65·2	78·40	3·0	2·5

The above results will probably inspire the reader to conduct similar tests under various conditions. The authors of the above paper do not give details concerning the method of gripping the specimens, etc., and it is therefore not possible to estimate within what measure of accuracy some of the figures come. That they form a valuable guide and reference cannot be doubted. The enormous amount of work entailed in such a research can only be appreciated by those who have attempted similar experiments.

Captain H. R. Sankey and Mr. J. Kent-Smith published a paper[2] entitled "Heat Treatment Experiments with Chrome-Vanadium Steel." The reader who wishes to do original work on this subject would do well to consult the journals of the scientific institutions or the pages of "Science Abstracts" for the last ten years. At the same time there is no need for the student who seeks to do new laboratory experiments to hesitate because someone else has done the same thing.

[1] Proceedings, Iron and Steel Institute, May, 1909.
[2] Transactions of the Institution of Mechanical Engineers, 1904.

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USEFUL CONSTANTS.

1 Inch = 25·40 millimetres.

1 Gallon = ·1604 cubic foot = 10 lb. of water at 62° F.

Weight of 1 lb. in London = 445,000 dynes.

One pound avoirdupois = 7000 grains = 453·6 grammes.

One cubic foot of water weighs 62·3 lb.

A column of water 2·3 feet high corresponds to a pressure of 1 lb. per in.

Absolute temp., $t = \theta°$ C. + 273° or $\theta°$F. + 460°.

One radian = 57·30 degrees.

To convert common into Napierian logarithms, multiply by 2·3026.

The base of the Napierian logarithms is $e = 2·7183$.

The value of g at London = 32·182 feet per sec. per sec.

LOGARITHMS.

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4 4	9 8	13 12	17 16	21 20	26 24	30 28	34 32	38 37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4 4	8 7	12 11	15 15	19 19	23 22	27 26	31 30	35 33
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3 3	7 7	11 10	14 14	18 17	21 20	25 24	28 27	32 31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3 3	7 7	10 10	13 12	16 16	20 19	23 22	26 25	30 29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3 3	6 6	9 9	12 12	15 15	18 17	21 20	24 23	28 26
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3 3	6 5	9 8	11 11	14 14	17 16	20 19	23 22	26 25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3 3	5 5	8 8	11 10	14 13	16 15	19 18	22 21	24 23
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	3 2	5 5	8 7	10 10	13 12	15 15	18 17	20 19	23 22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2 2	5 5	7 7	9 9	12 11	14 14	16 16	19 18	21 21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2 2	4 4	7 6	9 8	11 11	13 13	16 15	18 17	20 19
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8

LOGARITHMS.

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51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1		3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

ANTILOGARITHMS.

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·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2770	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

ANTILOGARITHMS.

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·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

Angle.		Chord.	Sine.	Tangent.	Co-tangent.	Cosine.			
Degrees.	Radians.								
0°	0	0	0	0	∞	1	1·414	1·5708	90°
1	·0175	·017	·0175	·0175	57·2900	·9998	1·402	1·5533	89
2	·0349	·035	·0349	·0349	28·6363	·9994	1·389	1·5359	88
3	·0524	·052	·0523	·0524	19·0811	·9986	1·377	1·5184	87
4	·0698	·070	·0698	·0699	14·3007	·9976	1·364	1·5010	86
5	·0873	·087	·0872	·0875	11·4301	·9962	1·351	1·4835	85
6	·1047	·105	·1045	·1051	9 5144	·9945	1·338	1·4661	84
7	·1222	·122	·1219	·1228	8·1443	·9925	1·325	1·4486	83
8	·1396	·140	·1392	·1405	7·1154	·9903	1·312	1·4312	82
9	·1571	·157	·1564	·1584	6·3138	·9877	1·299	1·4137	81
10	·1745	·174	·1736	·1763	5·6713	·9848	1·286	1·3963	80
11	·1920	·192	·1908	·1944	5·1446	·9816	1·272	1·3788	79
12	·2094	·209	·2079	·2126	4·7046	·9781	1·259	1·3614	78
13	·2269	·226	·2250	·2309	4·3315	·9744	1·245	1·3439	77
14	·2443	·244	·2419	·2493	4·0108	·9703	1·231	1·3265	76
15	·2618	·261	·2588	·2679	3·7321	·9659	1·218	1·3090	75
16	·2793	·278	·2756	·2867	3·4874	·9613	1·204	1·2915	74
17	·2967	·296	·2924	·3057	3·2709	·9563	1·190	1·2741	73
18	·3142	·313	·3090	·3249	3·0777	·9511	1·176	1·2566	72
19	·3316	·330	·3256	·3443	2·9042	·9455	1·161	1·2392	71
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22	·3840	·382	·3746	·4040	2·4751	·9272	1·118	1·1868	68
23	·4014	·399	·3907	·4245	2·3559	·9205	1·104	1·1694	67
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25	·4363	·433	·4226	·4663	2·1445	·9063	1·075	1·1345	65
26	·4538	·450	·4384	·4877	2·0503	·8988	1·060	1·1170	64
27	·4712	·467	·4540	·5095	1·9626	·8910	1·045	1·0996	63
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31	·5411	·534	·5150	·6009	1·6643	·8572	·985	1·0297	59
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33	·5760	·568	·5446	·6494	1·5399	·8387	·954	·9948	57
34	·5934	·585	·5592	·6745	1·4826	·8290	·939	·9774	56
35	·6109	·601	·5736	·7002	1·4281	·8192	·923	·9599	55
36	·6283	·618	·5878	·7265	1·3764	·8090	·908	·9425	54
37	·6458	·635	·6018	·7536	1·3270	·7986	·892	·9250	53
38	·6632	·651	·6157	·7813	1·2799	·7880	·877	·9076	52
39	·6807	·668	·6293	·8098	1·2349	·7771	·861	·8901	51
40	·6981	·684	·6428	·8391	1·1918	·7660	·845	·8727	50
41	·7156	·700	·6561	·8693	1·1504	·7547	·829	·8552	49
42	·7330	·717	·6691	·9004	1·1106	·7431	·813	·8378	48
43	·7505	·733	·6820	·9325	1·0724	·7314	·797	·8203	47
44	·7679	·749	·6947	·9657	1·0355	·7193	·781	·8029	46
45°	·7854	·765	·7071	1·0000	1·0000	·7071	·765	·7854	45°
								Radians.	Degrees.
			Cosine.	Co-tangent.	Tangent.	Sine.	Chord.	Angle.	

INDEX

D.

E.

F.

G.

H.

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